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COMPARATIVE EVALUATION OF MESOPHILIC AND THERMOPHILIC ANAEROBIC DIGESTION

PHASE I - TEMPERATURE TRANSITION STUDIES

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16. ABSTRACT

As part of a larger study on the comparison between mesophilic and thermophilic anaerobic digestion, a study of the operation of anaerobic systems under temperature transition was conducted. Systems seeded with domestic sewage sludge, but subsequently fed a chemically defined complex medium, were operated at 20- and 30-day detention times at 35°C. The temperature was raised to 55°C at rates varying from 0.25°C to 2.5°C per day in duplicate, parallel units. Irrespective of temperature rise rate, as soon as the temperature exceeded 45°C methane production shut down. The units were held at 45°C until recovery occurred. Once recovery of methane production ability occurred, transition to 55°C took place with little incident except for minor difficulty at 51°C. Data analysis indicated that rate of temperature rise had little effect on the total time required to obtain stable operation at 55°C; detention time had a minor effect with longer detention time yielding superior results.

Two other studies were conducted: a temperature drop study and a steady-state comparison between mesophilic and thermophilic operation. Sudden temperature drops below 50°C gave adverse effects. Steady-state mesophilic operation was superior, especially at lower detention times.

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing of research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

One of the major procedures for stabilization of municipal wastewater sludge is anaerobic digestion. Thermophilic digestion is of interest because it insures pasteurization of sludge. This report deals with the conversion of mesophilic digesters to thermophilic conditions and evaluates the potential effect of sudden temperature decreases on thermophilic digester performance.

E. Timothy Oppelt, Acting Director
Risk Reduction Engineering Laboratory

ABSTRACT

As part of a larger study on the comparison between mesophilic and thermophilic anaerobic digestion, a study of the operation of anaerobic systems under temperature transition was conducted. Systems seeded with domestic sewage sludge, but subsequently fed a chemically defined complex medium, were operated at 20- and 30-day detention times at 35°C. The temperature was raised to 55°C at rates varying from 0.25°C to 2.5°C per day in duplicate, parallel units. Irrespective of temperature rise rate, as soon as the temperature exceeded 45°C methane production shut down. The units were held at 45°C until recovery occurred. Once recovery of methane production ability occurred, transition to 55°C took place with little incident except for minor difficulty at 51°C. Data analysis indicated that rate of temperature rise had little effect on the total time required to obtain stable operation at 55°C; detention time had a minor effect with longer detention times yielding superior results.

A temperature drop study was conducted from 55°C to as low as 47.5°C. No adverse effect was observed until the temperature was reduced to less than 50°C. Washout of methane bacteria seemed to occur when the temperature was suddenly dropped below 50°C and the system detention time was less than 20 days.

Comparison of operation at 55°C vs. 35°C under steady-state at detention times ranging from 7.5 days to 30 days indicated that based on effluent volatile acids level, mesophilic operation was superior and that this superiority was greater at the lower detention times.

The organisms which function under thermophilic conditions appear to be present in mesophilic sludge but are not active at low temperature. When thermophilic conditions are brought about, the thermophilic organisms will multiply to an adequate level in several weeks.

This report was submitted in fulfillment of Grant No. CR811022 by Lehigh University under the sponsorship of the U.S. Environmental Protection Agency. This report covers a period from October, 1984 to April, 1986 and work was completed as of March 31, 1988.

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SECTION 1

INTRODUCTION

The purpose of this study was to conduct a comparative evaluation of the performance of anaerobic digestion systems under different temperature regimes. The temperature regimes chosen were those most commonly used in field installations (i.e. mesophilic 35°C and thermophilic 50-55°C). Evaluation of performance was in terms of a number of parameters including: stability of operation, degree of waste stabilization, dewaterability of digested sludge and odor.

The work has been divided into two phases. The first, which is reported on here, deals primarily with the operation of anaerobic digestion systems under situations of temperature transition. The second phase will deal with differences between system performance at steady state in the two temperature regimes.

The primary reason for conducting temperature transition studies revolves around the question of how to start up a thermophilic digestion system. The most efficient procedure is to seed with sludge from an operational thermophilic system. However, this material may not be readily available. In such a case it will be necessary to convert a mesophilic anaerobic digestion system to a thermophilic system. Because methane forming microorganisms are known to be quite sensitive to all environmental conditions, it was felt that a rapid change in temperature may not yield positive results. On the other hand, if a very low rate of adjustment of temperature is used, the anaerobic treatment system may be out of operation for a long period of time. Consequently, an evaluation was made here into the effect of temperature rise rate when converting from mesophilic to thermophilic operation.

Another question which was addressed in this study was the effect of temperature decreases on the performance of thermophilic systems. It is generally considered that thermophilic systems are more sensitive than mesophilic systems. Thus, small reductions in temperature may have severe consequences on thermophilic system performance. This part of Phase I of the study thus, incorporated experiments in which the temperature was intentionally and rapidly reduced to determine the magnitude of the effect on the thermophilic anaerobic systems. Finally, limited steady-state data on system performance were collected at 55°C and 35°C to determine if thermophilic anaerobic digestion is superior in performance to the conventional temperature 35°C. Much more extensive steady-state data were collected during Phase II and is reported on in the Phase II Report.

SECTION 2

CONCLUSIONS

1) Rate of temperature increase had little effect on the time required to reach stable operation at 55°C during conversion from mesophilic to thermophilic conditions.

2) The transition from mesophilic to thermophilic conditions occurs at 45°C as operation is interrupted (methane production halted) for several weeks when this temperature is reached.

3) Eventual recovery occurs indicating that thermophilic organisms exist in mesophilic sludge but are dormant.

4) It takes several days after reaching 45°C for the retardation to be fully manifest.

5) At longer detention time operation temperature transition effects are not as severe.

6) When the temperature is rapidly reduced from 55°C no effect on operation is manifest until the temperature is reduced below 50°C and the detention time below 20 days.

7) The temperature drop effect is probably not a reduction in the ability of the methane bacteria to process substrate but in the ability to reproduce.

8) Steady-state operation at 35°C was slightly superior to operation at 55°C at long detention times and clearly superior at short detention times.

SECTION 3

RECOMMENDATIONS

1) The data collected here gave some indication of a second retardation temperature slightly above 51°C, this should be investigated.

2) These studies should be repeated with a feed of sewage sludge to observe the effect of continuous reseeding from organisms in raw sludge.

3) The washout phenomenon observed when a temperature drop took place should be investigated.

4) Storage of thermophilic sludge at cold temperature (approx. 5°C) should be investigated as a method of saving thermophilic sludge for later use as seed for starting thermophilic digesters.

5) The data collected here indicated best performance of anaerobic digestion may be at temperatures in the range 40°C to 45°C. This should be studied in depth.

SECTION 4

EXPERIMENTAL PLAN AND DETAILS

Phase I contained four separate periods listed as A through D below:

A. Temperature Rise Rate Study

B. Steady State at 55°C and 35°C at 20 & 30 day detention times.

C. Temperature Drop Study

D. Steady State at 55°C & 35°C at detention times in the range from 20 to 7.5 days.

In all studies an artificial feed was used and feed and withdrawal was on a periodic batch basis. In all studies monitoring of the units was based on pH, alkalinity, volatile acids, gas volume and gas composition. Specific details of A follow, and specific details of B, C & D will be given as necessary when the results of these studies are presented.

TEMPERATURE RISE RATE

The major goal of Phase I of the study was to determine the effect of rate of temperature change on system performance during conversion from mesophilic conditions to thermophilic conditions. The basic plan used was to set up a series of bench scale units at 35°C, operate them to a steady state and then raise the temperature at various rates while maintaining a normal feeding pattern as long as possible.

A series of 1 liter bench scale anaerobic digestion systems were set up using digested sewage sludge from the anaerobic digester at the Allentown, PA Sewage Treatment Plant. The liquid volume used in each digester was 750 ml. Each unit was connected to a cylindrical gas collection tube which had been calibrated in increments of 10 ml. An acidified saturated salt solution was used as the confining fluid to trap the gas evolved. The confining fluid was held in a reservoir connected to the bottom of the gas collection tube. A diagram of this experimental arrangement is given in Figure 1. Throughout this study these units were operated on a batch feed and withdrawal basis. At each feeding interval a small portion of the contents of the unit were first withdrawn and then replaced by a like amount of fresh feed. The volume fed and withdrawn was a function of the hydraulic detention time at which the unit was being operated. Just prior to withdrawal, and also just after feeding, each unit was manually shaken for

approximately 10-15 seconds to insure complete dispersion of the contents. Thus these units were operated at identical solids and hydraulic retention times (SRT=HRT).

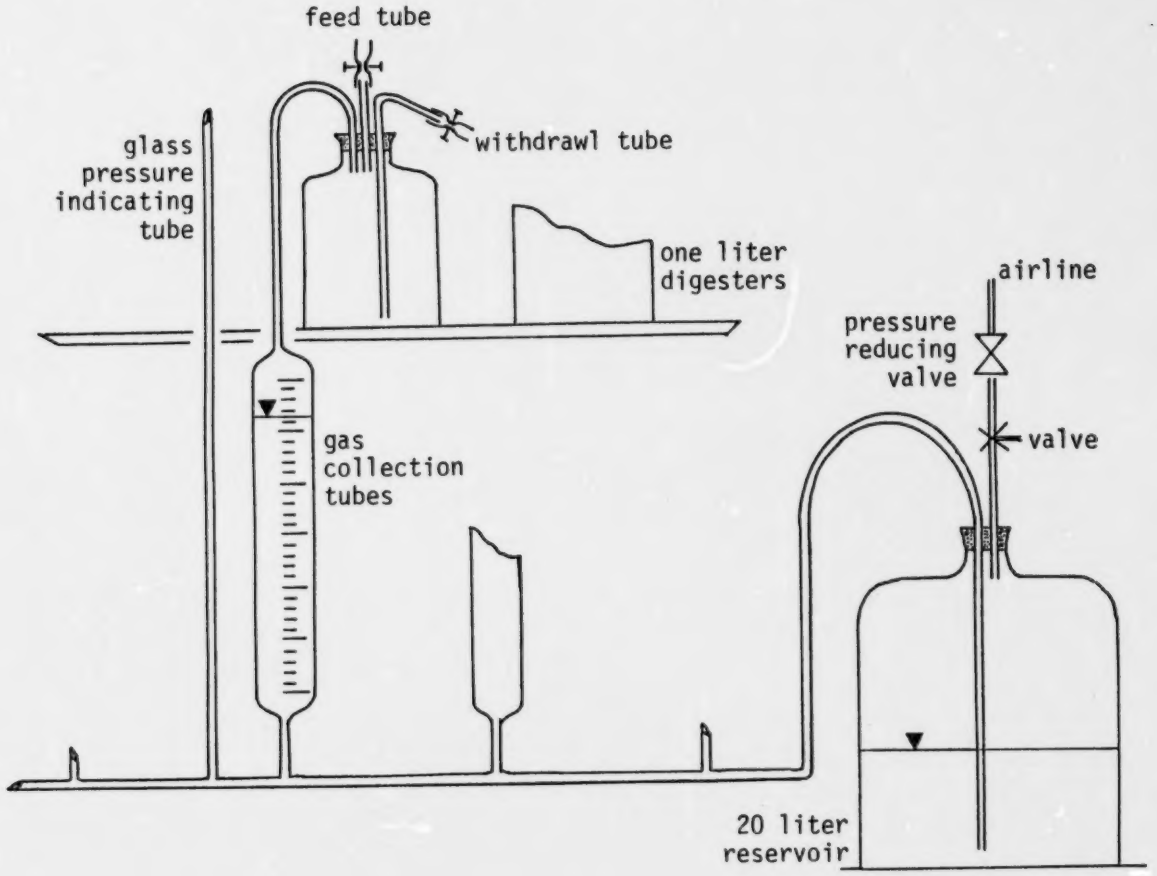
A total of 20 units were set up, ten at each detention time used. In addition, units were operated in pairs. This provided for four sets of units at each detention time in which the temperature would be raised plus one pair as a control. The control units were maintained at 35°C. The units were numbered 1 through 10 with duplicates identified as A & B. The four rates of temperature rise used were 1°C, 2°C, 3.5°C and 5°C per feeding period (the term feeding period will be defined below). Table 1 lists the numbering system used and the conditions of operation for each unit.

TABLE 1. IDENTIFICATION OF UNITS IN TEMPERATURE RISE STUDY

Identification	Detention Time	Temperature Rise Rate
1A-1B	30 days	2°C
2A-2B	30 days	1°C
3A-3B	30 days	5°C
4A-4B	20 days	2°C
5A-5B	30 days	3.5°C
6A-6B	20 days	5°C
7A-7B	20 days	3.5°C
8A-8B	20 days	1°C
9A-9B	30 days	0°C
10A-10B	20 days	0°C

All of the units were set up in a temperature controlled room maintained at 35± 0.1°C. The units in which the temperature was to be raised were in addition immersed in temperature controlled water baths. Each consisted of a 10 gallon glass aquarium insulated with sheets of polystyrene on all vertical sides. Beads of polystyrene were placed on top of the water surface to act as insulation. Variable setting aquarium heaters were used to raise the temperature above amibient levels in the room (35°C). The water in the bath was kept in circulation by bubbling a small quantity of air continuously into the water. Prior to actually conducting the experiments detailed below, the settings on the thermostats were manually calibrated. Mercury thermometers were inserted into 1 liter bottles containing 750 ml of water. These were placed in the water bath and used to calibrate heater setting; and thereafter for temperature measurement. The thermometer units were kept in the water baths throughout the study to monitor the temperatures. Eight water baths were used. Each contained a pair of bench scale anaerobic units and the temperature measurement bottle.

Figure 1. Batch daily feed digester system. Black triangles indicate fluid levels.



As indicated above, these units were originally started with digested sludge. It had been planned to use raw sludge from the Allentown Sewage Treatment Plant as the feed during these tests. The initial detention times chosen were 7.5 and 15 days. After several weeks it became apparent that good operation at these conditions (35°C, 7.5 & 15 day detention time) was not achieved. This was based on high levels of volatile acids in the units (1000 mg/l). Consequently the detention times were increased to 20 and 30 days. Improvement was observed (the volatile acids fell to about 500 mg/l) but operation was not satisfactory because of the high volatile acids level. It was decided that an inhibitory substance or a nutritional deficiency was manifest in the Allentown Treatment Plant. Consequently it was decided to use an artificial feed in these studies. The feed chosen was a commercial product "Carnation Instant Breakfast" suspended in whole milk. It was chosen because when mixed with whole milk in the recommended proportion (1 envelope per 8 fluid ounces of milk) it had a fat, carbohydrate and protein content similar to that of raw sludge. In addition, it contained most of the organic and inorganic nutrients required by microorganisms. The feed was, in addition, supplemented with several inorganic materials for which methane fermenting organisms have a high demand, i.e., Fe, Co, Ni. A complete analysis of the feed is given in Table 2. Within a few weeks of this change in feed, the volatile acid level in the digester effluents was consistently in the range of 100 to 200 mg/l, and stable gas production was observed. The units were continued in operation for several months to insure washout of the original seed material.

TABLE 2. FEED USED IN STUDY

Na_2HPO_4	25 mg/l
Carnation Instant Breakfast	6.5 g/l
NH_4HCO_3	1.9 g/l
$CoCl_2$	1 mg/l as Co
$FeCl_2$	150 mg/l
Ammonium Molybdate	0.02 mg/l
$MnCl_2$	0.4 mg/l
Boric Acid	0.01 mg/l
Sodium Tungstate	0.02 mg/l
NaCl	0.2 g/l
$MgCl_2$	0.1 g/l
Nickel Acetate	2 mg/l
K_2SO_4	0.2 g/l
Milk	66.6 ml
Yeast Extract	10 mg/l
Bethlehem Tap H_2O	1 liter

After the washout period was complete (>3 HRT's), the temperature change period was initiated. The volume of feed required for the detention times used corresponds to 25 ml per day at a 30 day HRT and 37.5 ml per day at a 20 day HRT. It was felt that these volumes were too small to be fed

accurately. Thus during this study the 30 day HRT unit was fed 50 ml once every 2 days and the 20 day HRT units were fed 75 ml once every 2 days. It was indicated above that nominal temperature changes per feeding period were to be used. Thus a feeding period represents the period of 2 days after a feeding event.

In conducting the temperature rise study the following procedure was used. At the beginning of a feeding period the heater in the water bath of the appropriate units was adjusted based on the prior calibration and the normal once per 2 day withdrawal and feed took place. Periodically over the next 2 days the temperature in the bath was checked to insure that it was not above or below the new set point. At the end of the 2 day period a comparison was made between the gas production from the last 2 days and that from the control units (which were maintained at 35°C). If gas production was close to that of the control unit the temperature was again raised and the unit was given a normal feeding. If gas production was significantly less than in the control unit the temperature was not raised and the units were not fed. The units were not fed again until gas production data indicated that most of the previous feed had been converted to methane and carbon dioxide. The temperature was not raised again until most or all of the feed added during the last feeding was consumed in the standard 2 day period. It should be appreciated that judgement of the experimentor was used in determining when to feed and when to raise the temperature. No firm quantifiable rules were employed. As each run progressed and experience was gained the decisions on feeding and temperature change were modified.

Each time a withdrawal was made from a unit the digester mixed liquor was analyzed for pH, alkalinity and volatile acids. Daily gas production was determined and at the end of each feeding period gas analysis for methane and carbon dioxide was conducted. Alkalinity, pH and volatile acids were monitored by the procedures given in Standard Methods(1) (volatile acids by distillation); gas analysis was conducted using a Fisher Gas Partioner(2).

STUDIES B, C, AND D

Over a three month time period the temperature of each unit except the controls was raised to 55°C. At that time it was decided to continue operation of these units at 55°C & 35°C respectively to establish a comparison between operation at these temperatures with this feed and at these 2 detention times.

Subsequent to this steady state period, a study was conducted in which the temperature was suddenly dropped by various amounts while normal operation i.e., feed and withdrawal were maintained. This study determined the effect that a sudden loss of heat supply could have on the operation of a thermophilic digester.

Only some of the 16 units being maintained at 55°C were used in the temperature drop study. The remainder were used in a study in which the detention times of the 55°C and the 35°C units were reduced down to as low as 7.5 days. The purpose of this study was again to obtain a comparison

between operation of units in parallel at the two temperatures but at much lower detention times.

SECTION 5

RESULTS

TRANSITION TO THERMOPHILIC TEMPERATURES

The results of this study are presented in the 40 figures which follow. Some of these figures give gas production as a function of time and temperature, while others provide plots of digester volatile acids versus time and temperature. The results are discussed below grouped primarily according to rate of temperature rise and secondarily according to detention time. In the plots of gas production each vertical bar represents one feeding period. During periods of good operation a feeding period represents 2 days so the bar has 2 sections (unmarked and crosshatched). The unmarked section is gas production during the first day after feeding. The crosshatched section represents the gas production on the second day after feeding. When retarded operation occurred each bar had more than 2 sections as it required more than 2 days to consume the feed. Each section of the bar, either unmarked or crosshatched represents one day. Thus, if a vertical bar has 6 sections it means it required 6 days to consume a standard feeding. For the first 20 days (10 feeding periods) of this study no temperature rise took place. These data give an indication of normal operation at 35°C prior to initiation of the temperature rise.

Rate of Temperature Rise = 0°C - 30 Day Detention Time

Figures 2-5 present the performance of the 30 day detention time controls during the 100 days of this study (units 9A and 9B). Gas production was 584 ± 37 ml for 9A and 574 ± 36 ml for 9B. Approximately 90% of the gas was produced during the first day. The abnormally high production of gas on day 80-82 for 9A was due to a minor leak which occurred on that day. Volatile acids averaged <200 mg/l, with occasional excursions near 400 mg/l.

Rate of Temperature Rise = 0°C - 20 Day Detention Time

Figures 6-9 present the performance of the 20 day detention time controls (units 10A & 10B). Results obtained were similar to those for the 30 day controls. Gas production was consistently good and volatile acids low; <200 mg/l. However, one unusual event which occurred was that during the period day 26-28 unit 10A was killed when the acid-salt confining fluid accidentally gained entrance to the unit. A new unit was immediately set up using previous days effluent from units 10A & 10B which had been stored in the refrigerator at 4°C. It can be seen that this new unit started up almost instantaneously. This phenomenon of being able to start an anaerobic

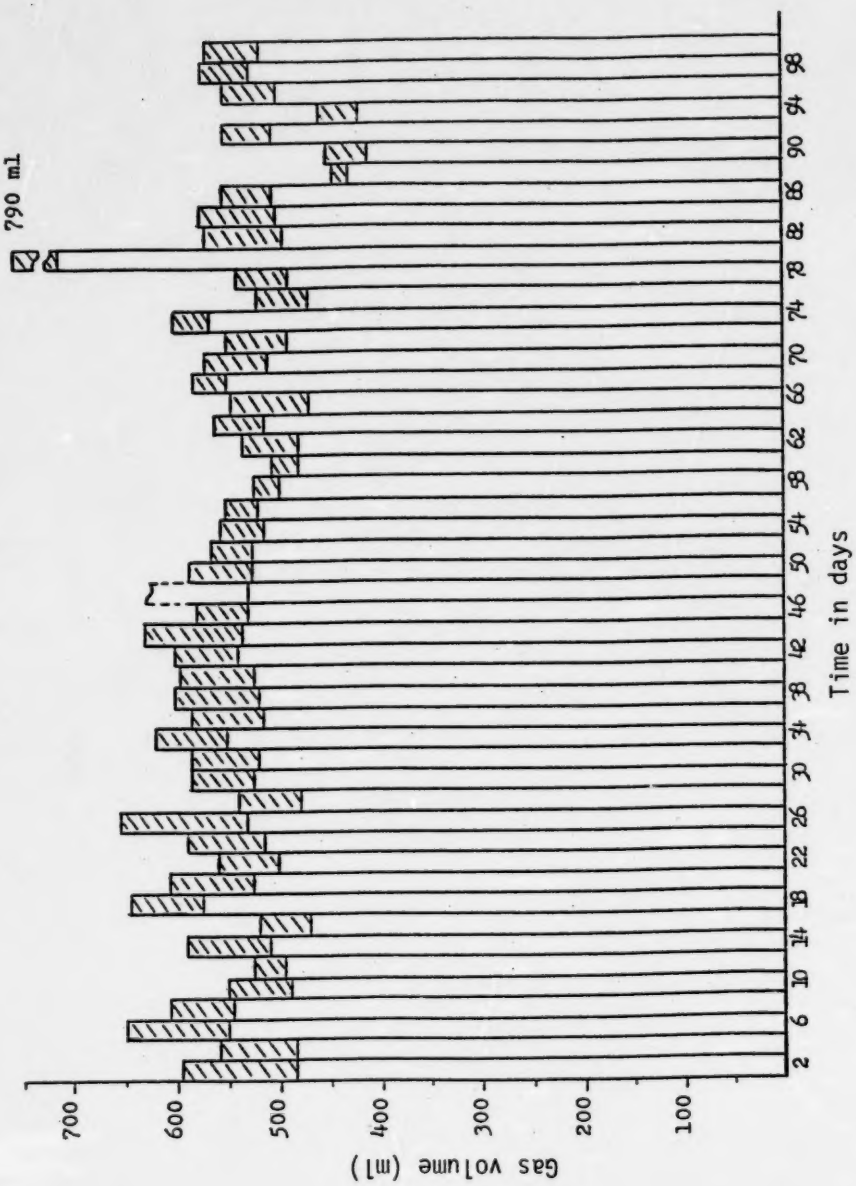


Figure 2. Gas production from unit 9A (control): 30 day detention time.

Figure 3. Gas production from unit 9B (control): 30 day detention time.

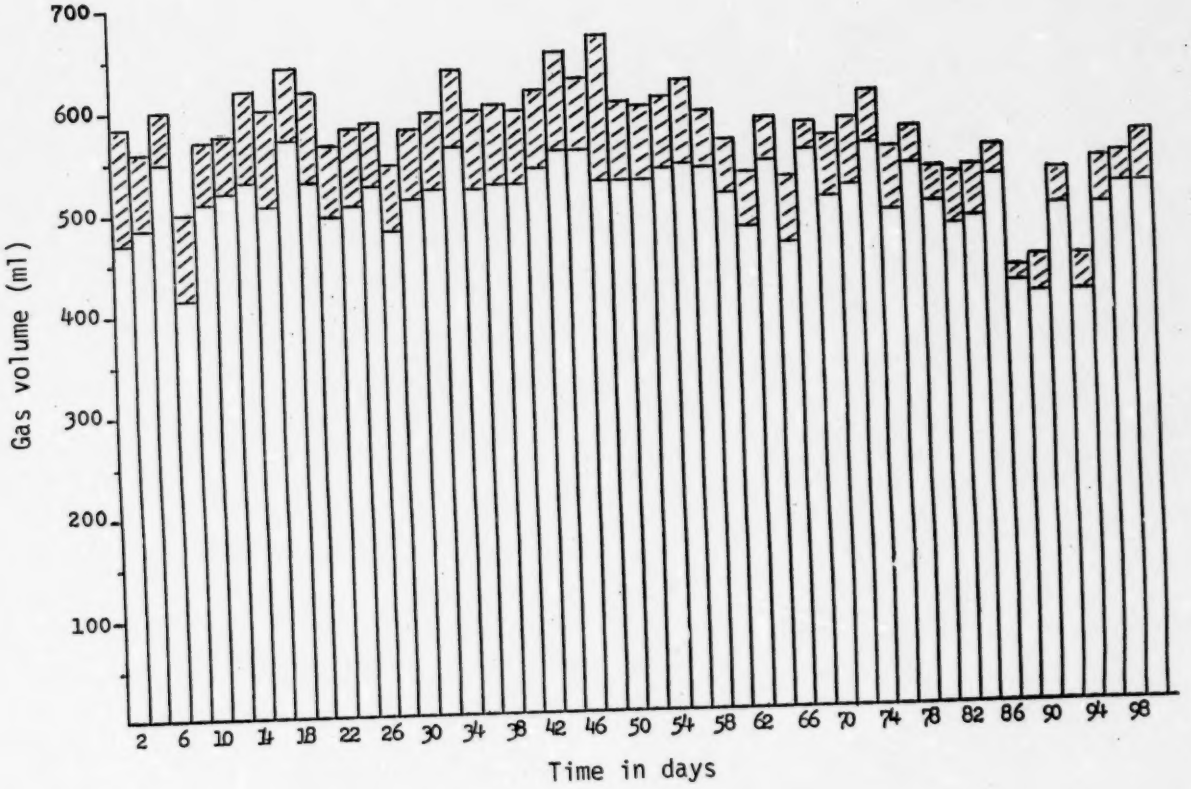


Figure 4. Temperature and volatile acids concentration versus time for unit 9A (control): 30 day detention time.

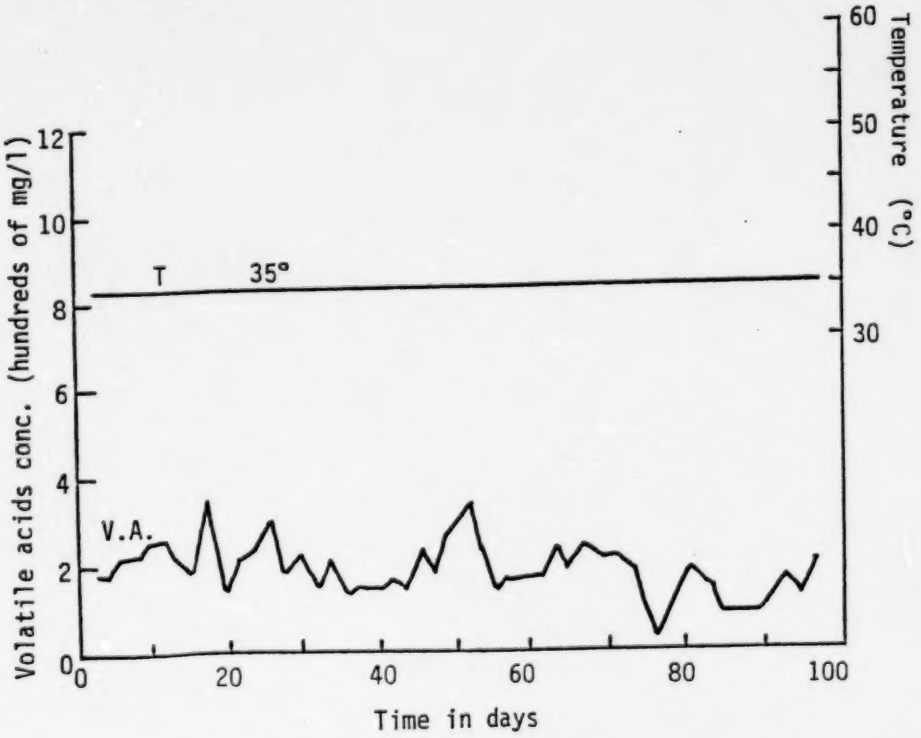


Figure 5. Temperature and volatile acids concentration versus time for unit 9B (control): 30 day detention time.

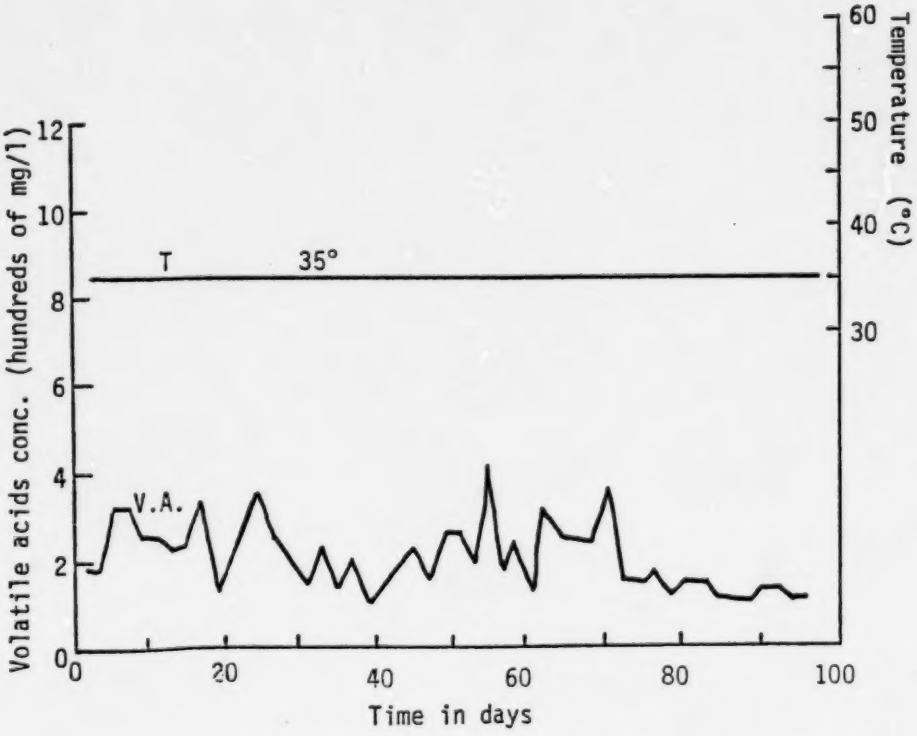


Figure 6. Gas production from unit 10A (control): 20 day detention time.

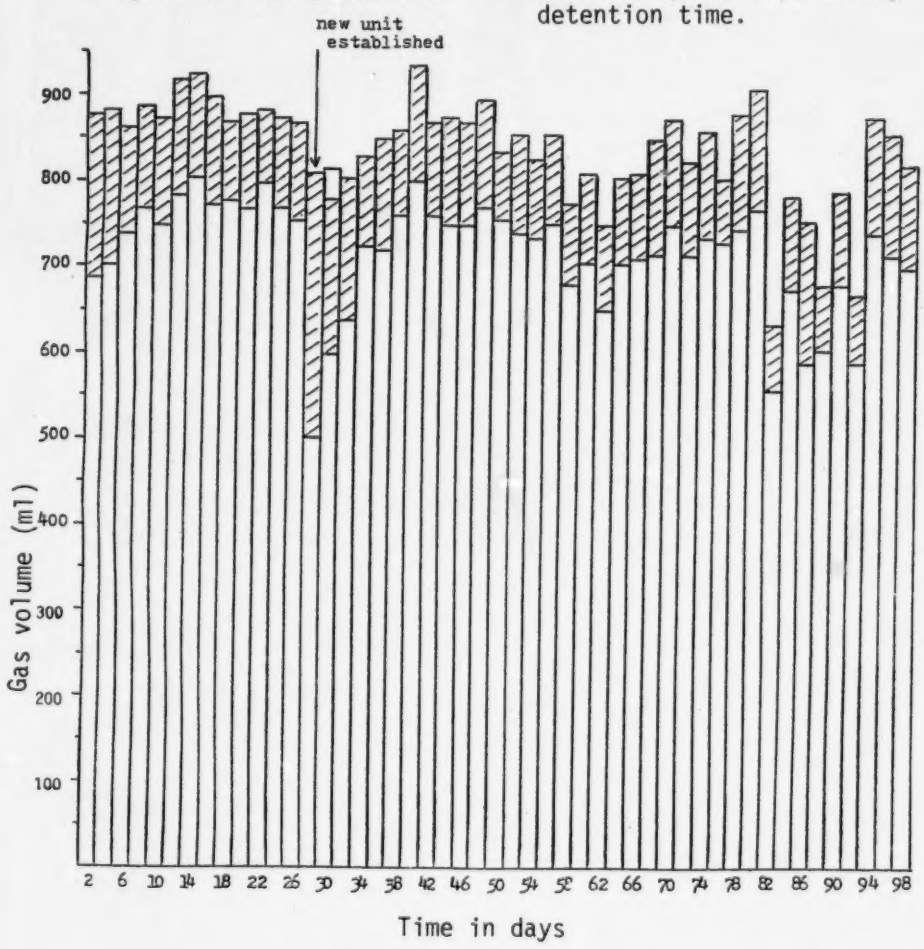


Figure 7. Gas production in unit 10B (control): 20 day detention time.

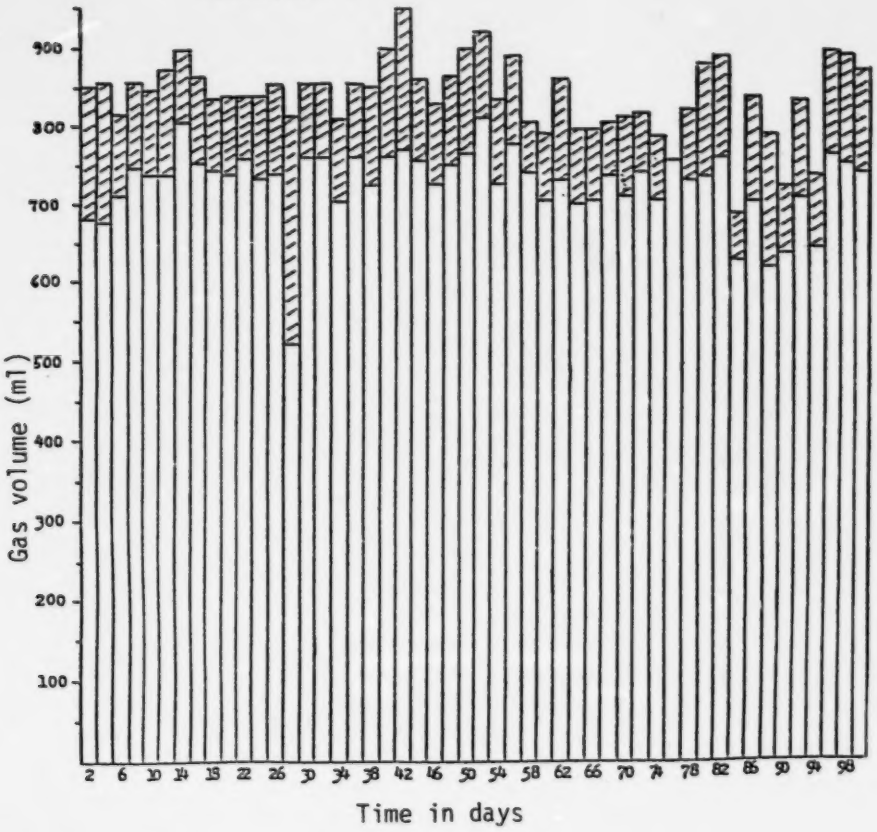


Figure 8. Temperature and volatile acids concentration versus time for unit 10A (control): 20 day detention time.

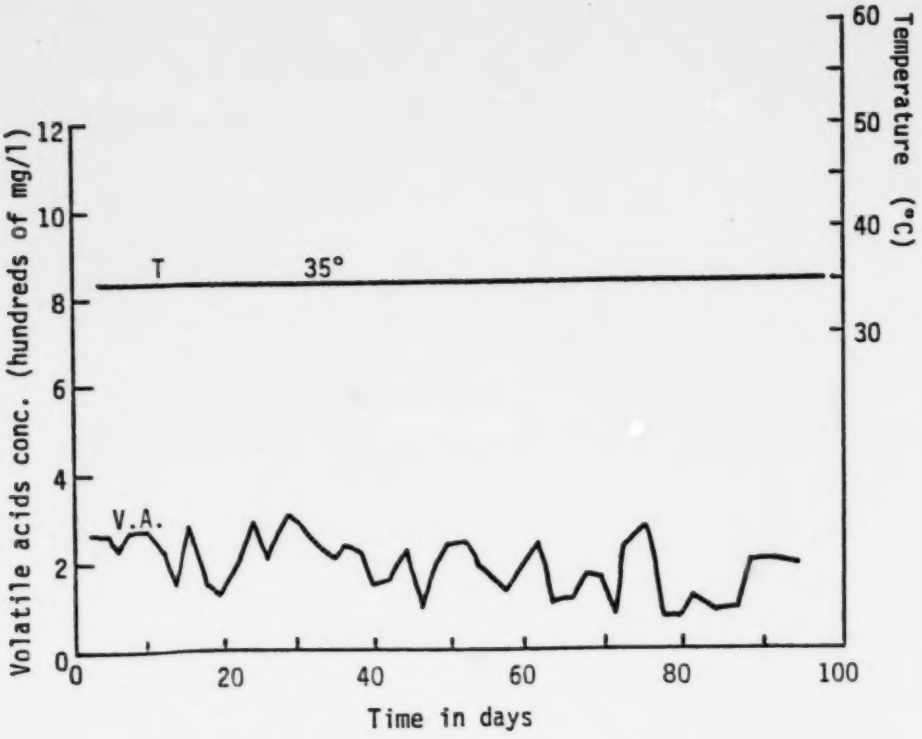


Figure 9. Temperature and volatile acids concentration versus time for unit 10B (control): 20 day detention time.

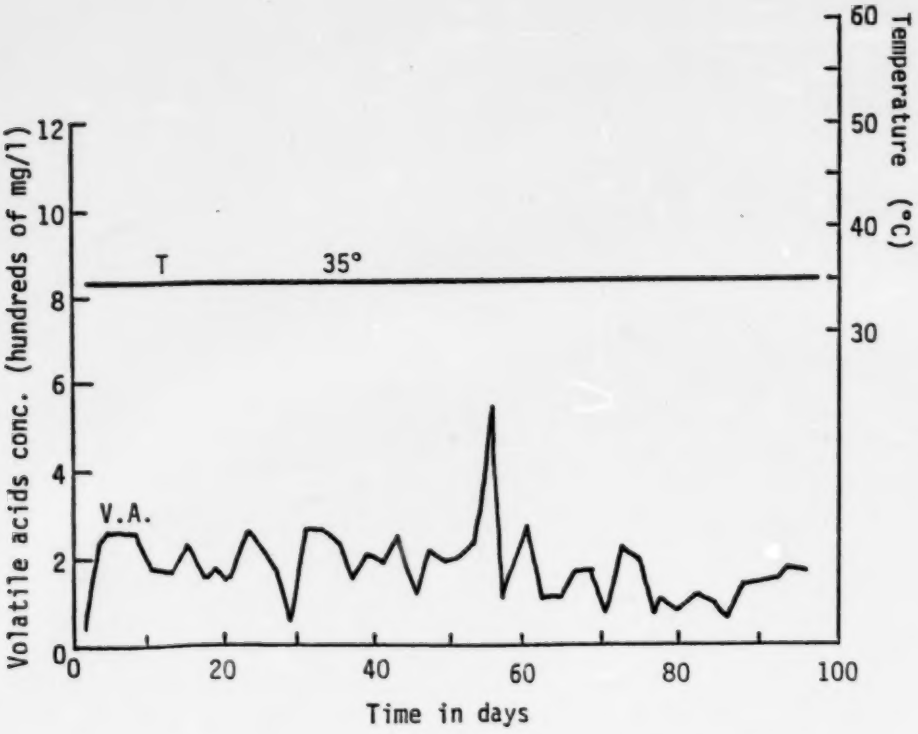
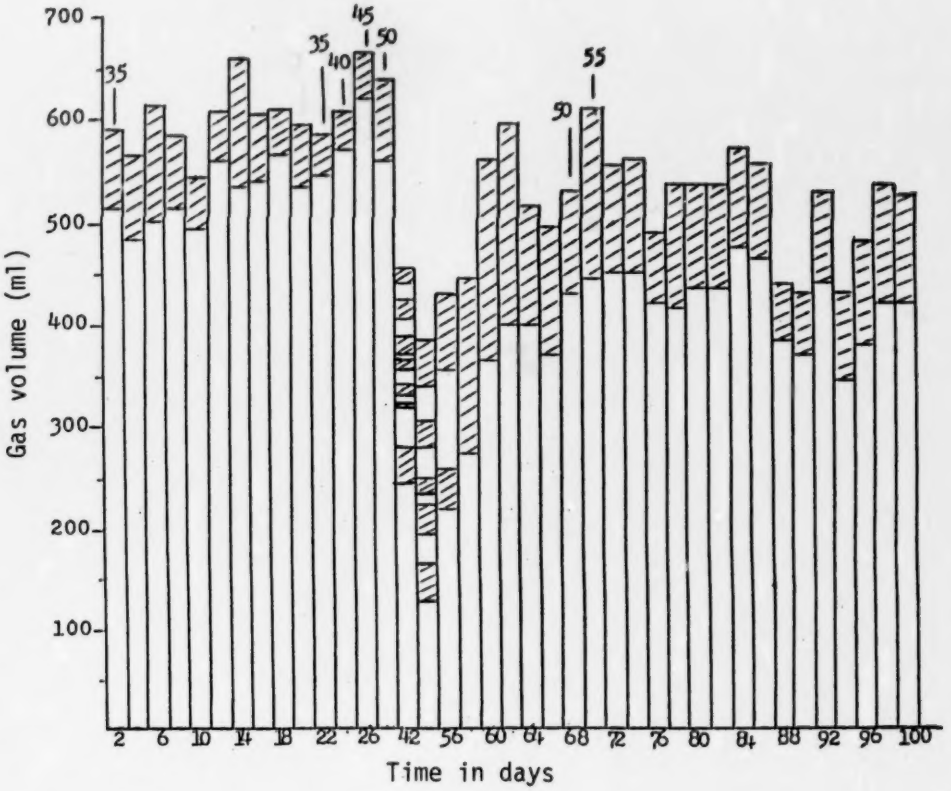


Figure 10. Gas production in unit 3A ($5^{o}C$ increment): 30 day detention time.



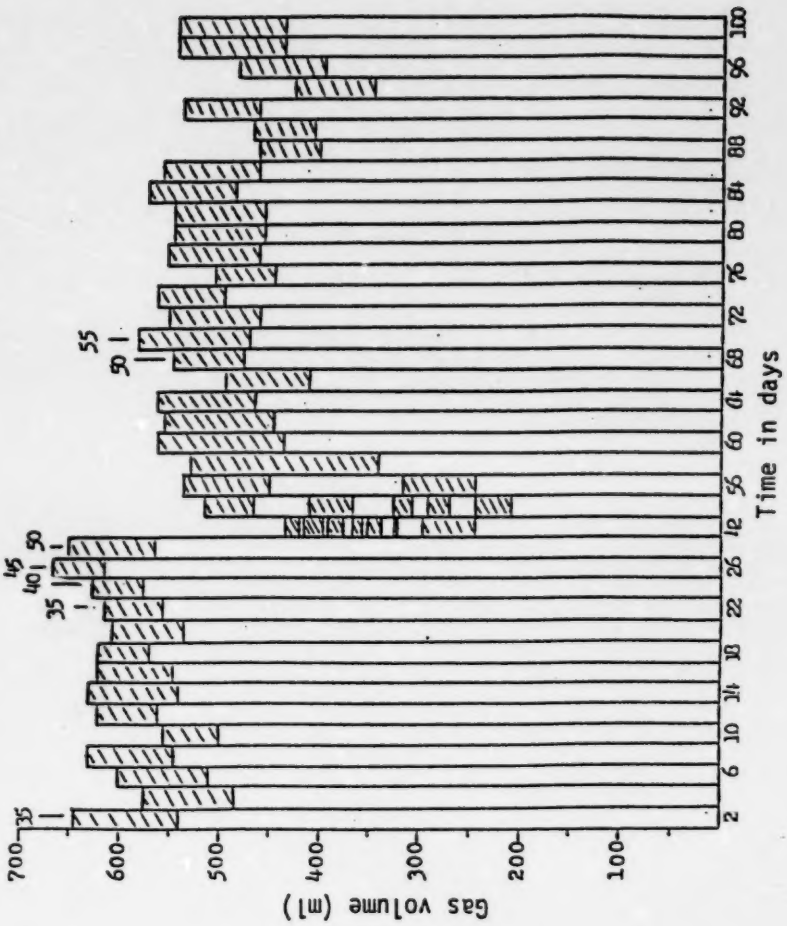


Figure 11. Gas production in unit 3B (5°C increment): 30 day detention time.

Figure 12. Temperature and volatile acids concentration versus time for unit 3A (5°C increment): 30 day detention time.

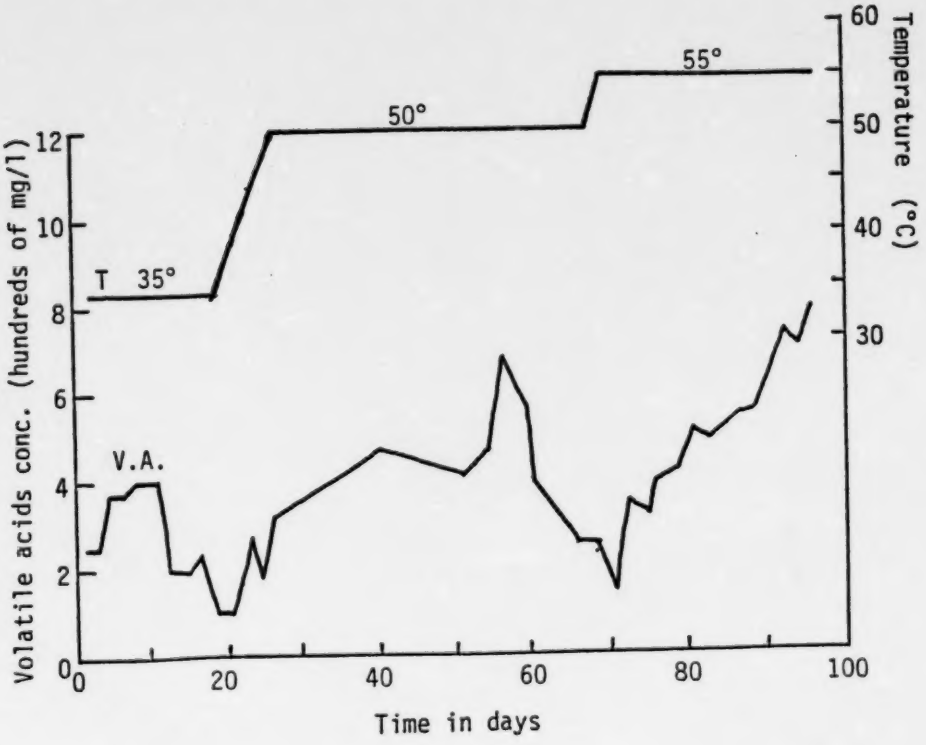
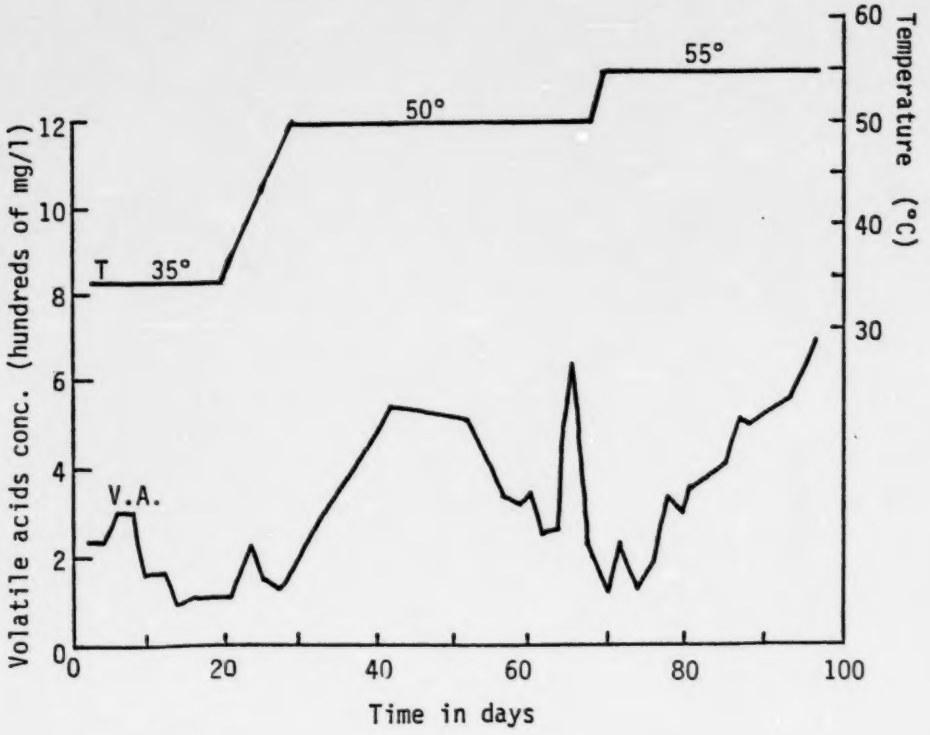


Figure 13. Temperature and volatile acids concentration versus time for unit 3B (5°C increment): 30 day detention time.



digestion unit rapidly from digester effluent or mixed liquor stored at 4°C was observed several other times during this study. The average gas production from unit 10B was 837 ± 45 ml. About 15% of the gas production took place on the second day of the feeding period. Data for 10A were not averaged because of its replacement as detailed above. The ratio of gas production for the 20 day detention time to that for the 30 day units was 1.45 which is close to the theoretical value of 1.5. As indicated above volatile acids were always low except for an excursion to 500 mg/l in unit 10B on day 54.

Rate of Temperature Rise = 5°C - 30 Day Detention Time

Figures 10-13 present the data for the 5°C rate of rise. It can be seen that the units (3A & 3B) exhibited similar performance. At 40°C and 45°C, performance was as good or even better than the control units (35°C). However the transition from 45°C to 50°C created an adverse situation both with respect to the acid formers and methane formers. The effect was not immediately apparent in the first feeding period after the transition except in the slight shift in proportion of gas production on the first and second days (90% first day at 45°C, 80% first day 50°C). However, the units essentially shut down during the second feeding period after the temperature reached 50°C. It was not until day 58 (a period of 30 days) that these units could function at the normal 2 day feeding period. Even then the proportion of gas production during the first day was low. By day 68 the units exhibited nearly normal operation and low volatile acids. On day 69-70 the temperature was raised to the target of 55°C. Over the next 30 days the normal 2 day feeding period could be maintained but the volatile acids gradually increased (almost linearly) from 200 mg/l to 800 mg/l.

Rate of Temperature Rise = 5°C- 20 Day Detention Time

Figures 14-17 depict the results for these conditions. Similar results to those obtained at 30 day detention time were observed. Until 45°C no adverse effect was noted. A small drop in gas production and concomitant rise in volatile acids occurred during the first feeding period after 50°C was reached. During the second feeding period a significant shutdown occurred. Both methane and acid formers were affected but the effect on the former was much greater. It was not for another 40 days (day 26 - day 66) that the normal 2 day feeding period could be resumed, and 10 more days were required until it was felt that it was safe to raise the temperature to 55°C. The shift to 55°C was not as uneventful as at the longer detention time. Some retardation which resulted in modest increases in volatile acids occurred. To keep the volatile acids under control a 4 day feed period was used during day 90-94. Even so volatile acids were quite high, 1100 mg/l in unit 6A while they were low, 450 mg/l in unit 6B. A short temperature excursion to almost 60°C due to a malfunction of the heater in the 6A-6B water bath may be to blame for the poorer performance of these units.

Rate of Temperature Rise = 3.5°C - 30 Day Detention Time

As illustrated in figures 18-21 the major adverse effect was manifest when the transition from 45.5°C to 49°C occurred. As before in the first

Figure 14. Gas production from unit 6A ($5^{o}C$ increment): 20 day detention time.

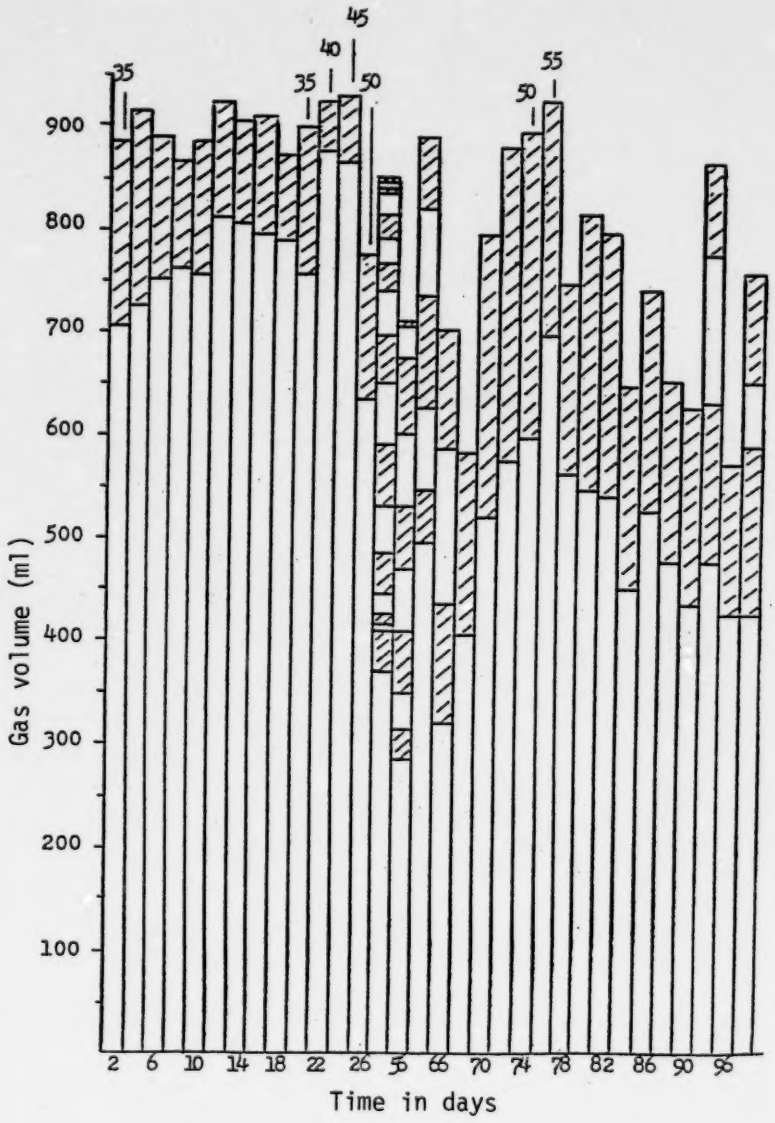


Figure 15. Gas production from unit 6B ($5^{o}C$ increment): 20 day detention time.

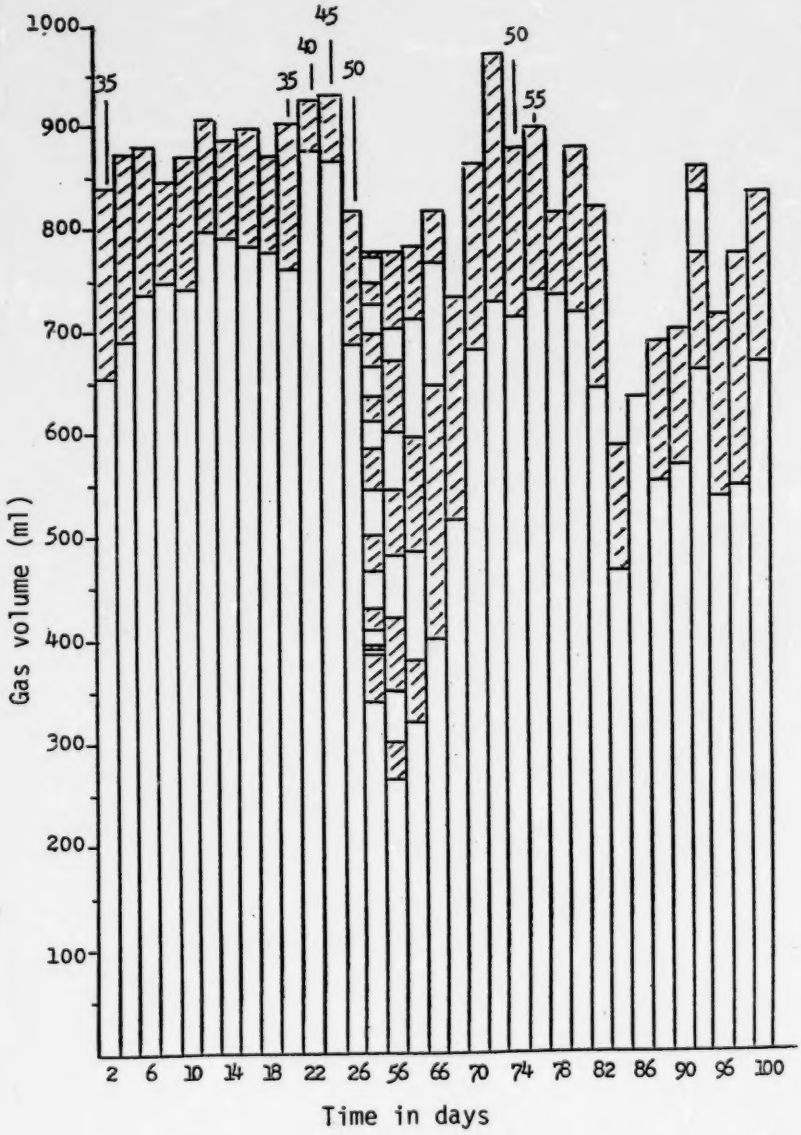


Figure 16. Temperature and volatile acids concentration versus time for unit 6A (5°C increment): 20 day detention time.

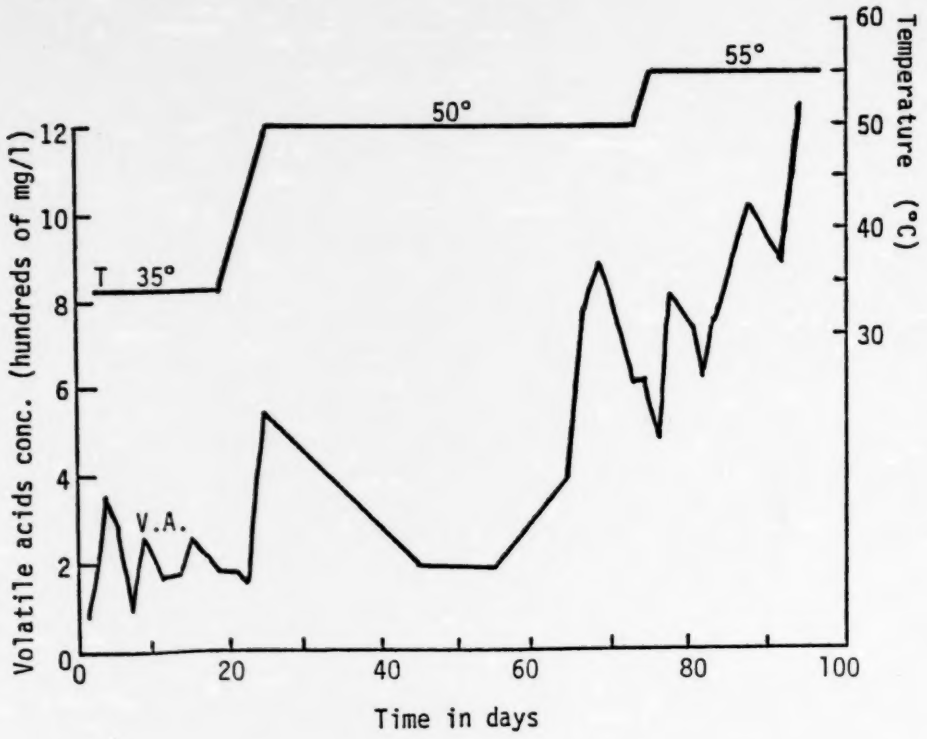


Figure 17. Temperature and volatile acids concentration versus time for unit 6B (5°C increment): 20 day detention time.

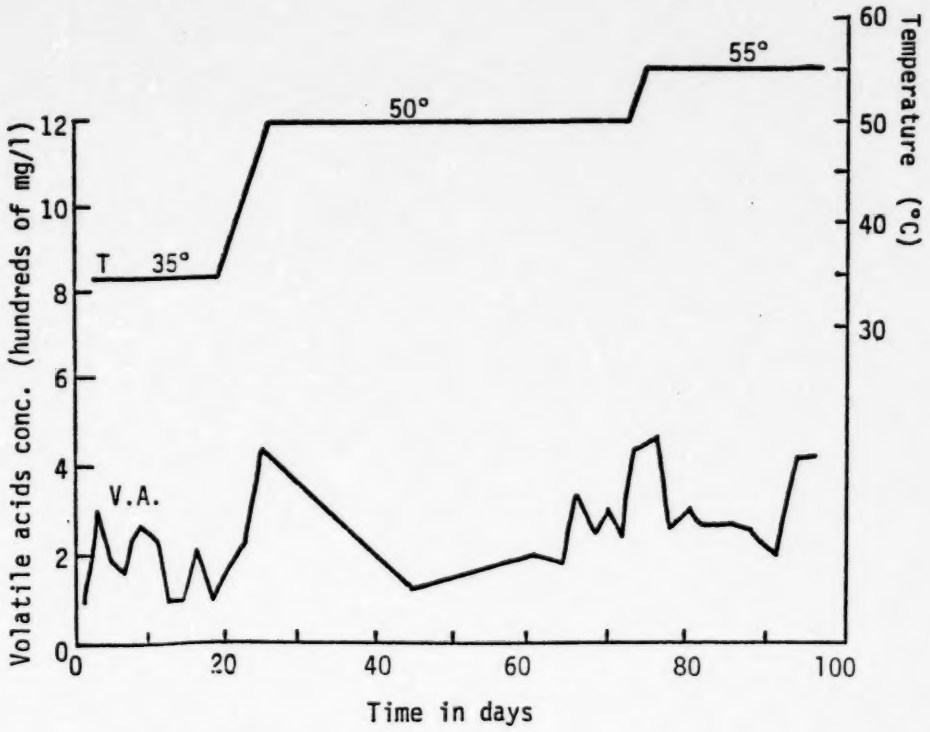
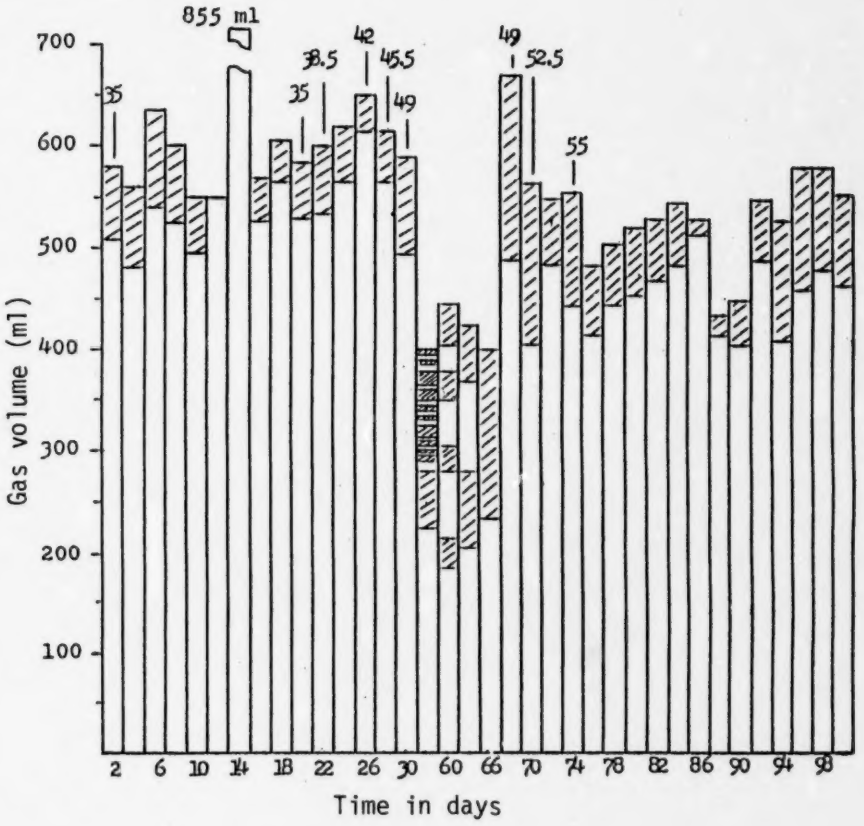


Figure 18. Gas production from unit 5A (3.5°C increment): 30 day detention time.



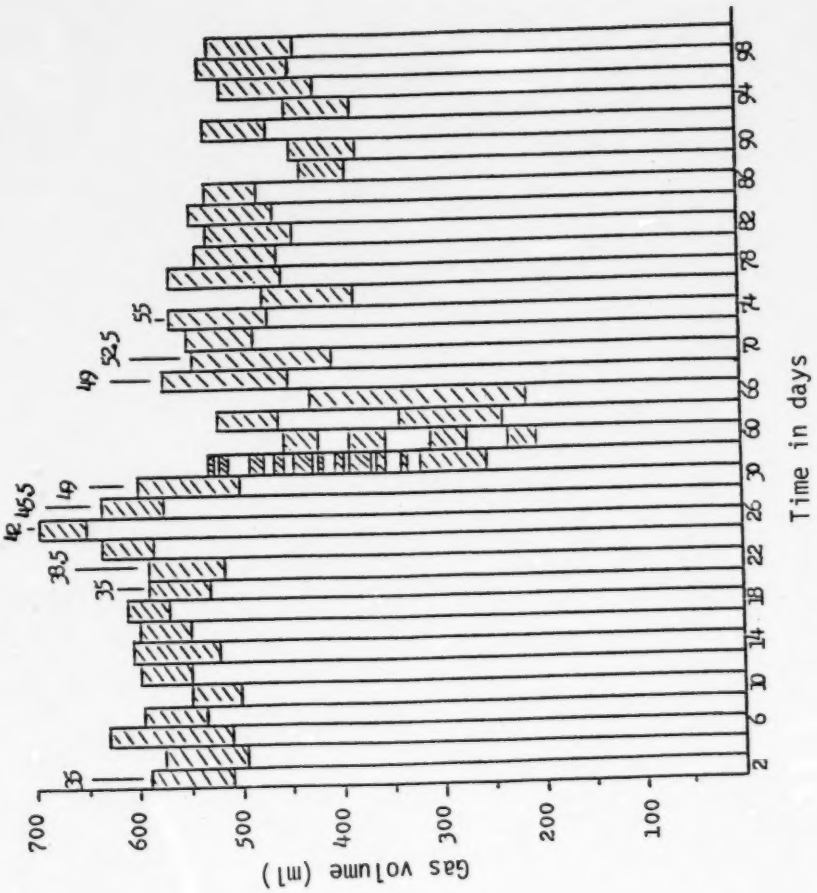


Figure 19. Gas production from unit 5B (3.5°C increment): 30 day detention time.

Figure 20. Temperature and volatile acids concentration versus time for unit 5A (3.5°C increment): 30 day detention time.

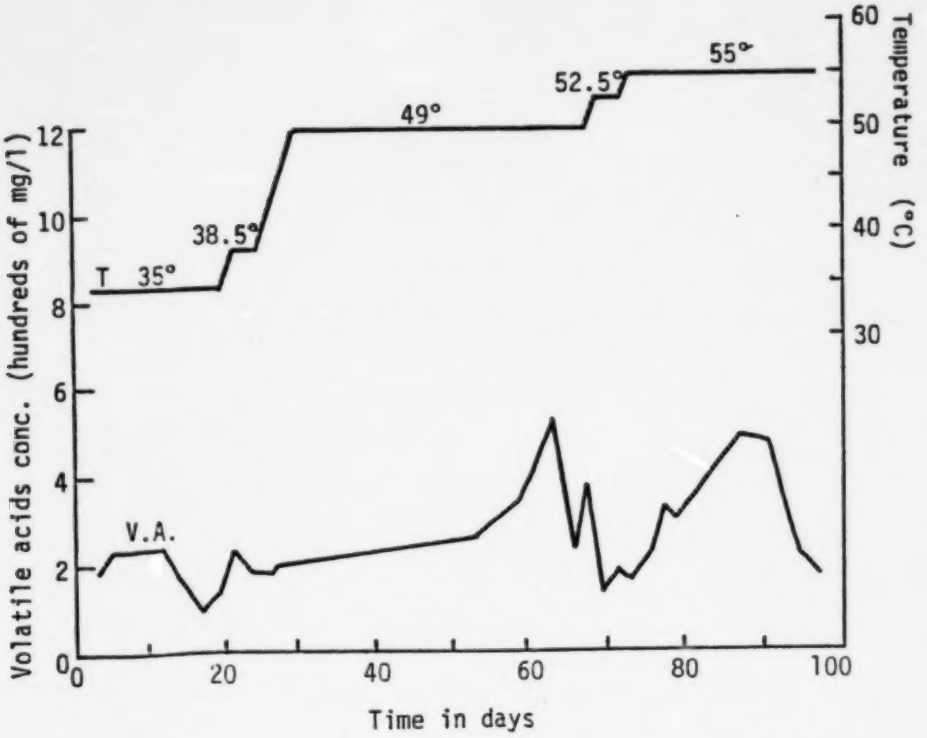
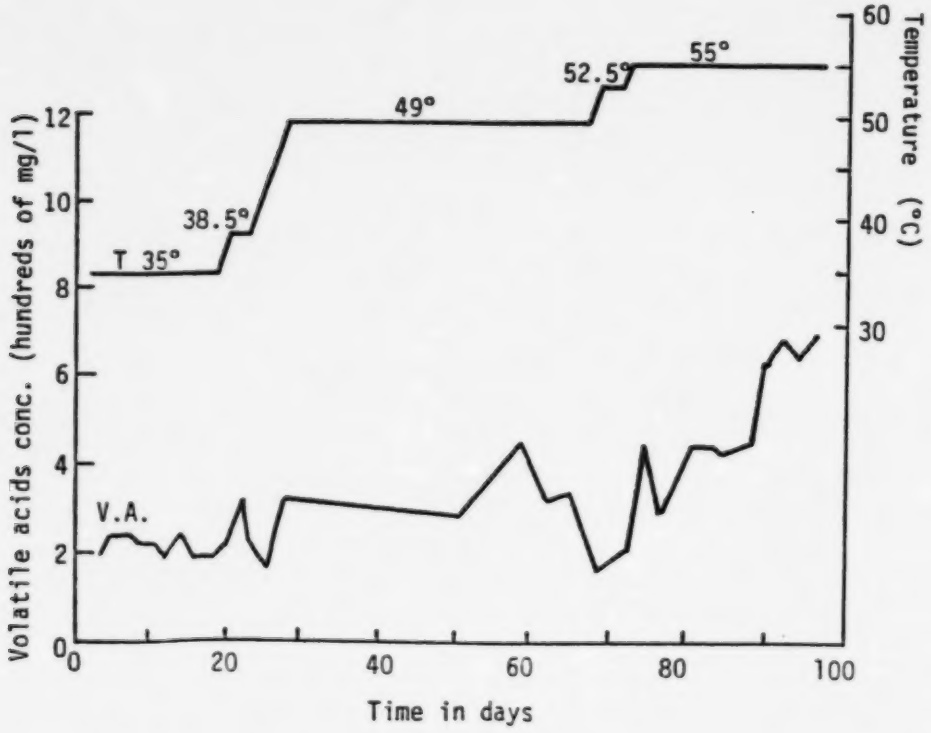


Figure 21. Temperature and volatile acids concentration versus time for unit 5B (3.5°C increment): 30 day detention time.



feeding period after the transition to 49°C, only minor difficulty was observed but during the second feeding the full effect of the higher temperature was observed. It was 24 days before the normal 2 day feeding pattern could be resumed. Recovery was excellent as the transition to 52.5°C was made in 4 days and that to 55°C in another 4 days. At 55°C some retardation was observed as volatile acids started to rise. The volatile acids returned to normal in unit 5A (200 mg/l) but became elevated (700 mg/l) in unit 5B.

Rate of Temperature Rise - 3.5°C - 20 Day Detention Time

Figures 22-25 illustrate a pattern similar to that observed at the longer detention time. All was satisfactory until the transition to 49°C from 45.5°C. In this case the initial result of the change was more severe than at the 30 day detention period. It took 30 days until the normal feeding pattern could resume and 12 more days until a transition to 52.5°C could take place. In another 2 days a transition to 55°C took place, but this may have been premature. A rapid rise in volatile acids occurred which was brought under control by going through a single 4 day feeding period. Eventually the normal feeding of once per 2 days could be continually used, and volatile acid levels dropped to the range 200 to 400 mg/l. An interesting observation is that at 55°C the second day gas volume was close to 25% of the total versus about 15% at 35°C.

Rate of Temperature Rise - 2°C - 30 Day Detention Time

Figure 26-29 illustrates the familiar pattern except that the use of a slower rate of temperature rise allows finer delineation of the temperature effect. Under these conditions the initial adverse effect is noted at the transition from 45°C to 47°C. Again the full effect is delayed for at least one feeding period. It took only 14 days till the normal 2 day feed period could be reinstated, however, 16 more days passed before the transition to 49°C occurred. In retrospect this was excessive as volatile acid levels were normal 8 days earlier. However, at this stage the investigators had become sensitized to being optimistic about the ability of these systems to avoid adverse effects of temperature change. After 6 days at 49°C the temperature was pushed to 55°C in the next 6 days. Volatile acids rose and gas production fell temporarily, but were soon reasonably satisfactory without the need to depart from the 2 day feed schedule.

Rate of Temperature Rise - 2°C - 20 Day Detention Time

With these units, much more severe retardation was observed (Figures 30-33) than at the 30 day detention time. It was decided not to stop at 47°C but to go on to 49°C. This caused a 36 day period in which the 2 day feed cycle could not be used and a total period of 40 days before another temperature increase (to 51°C) was attempted. At 53°C some minor retardation occurred and 55°C was reached in 6 more days. However, it was necessary to twice use a 4 day feed cycle before the units operated normally at 55°C. In this situation the A unit did not do as well as the B unit. Volatile acids in A were 800 mg/l while they were 300 mg/l in B after steady operation at 55°C was achieved.

Figure 22. Gas production from unit 7A (3.5°C increment): 20 day detention time.

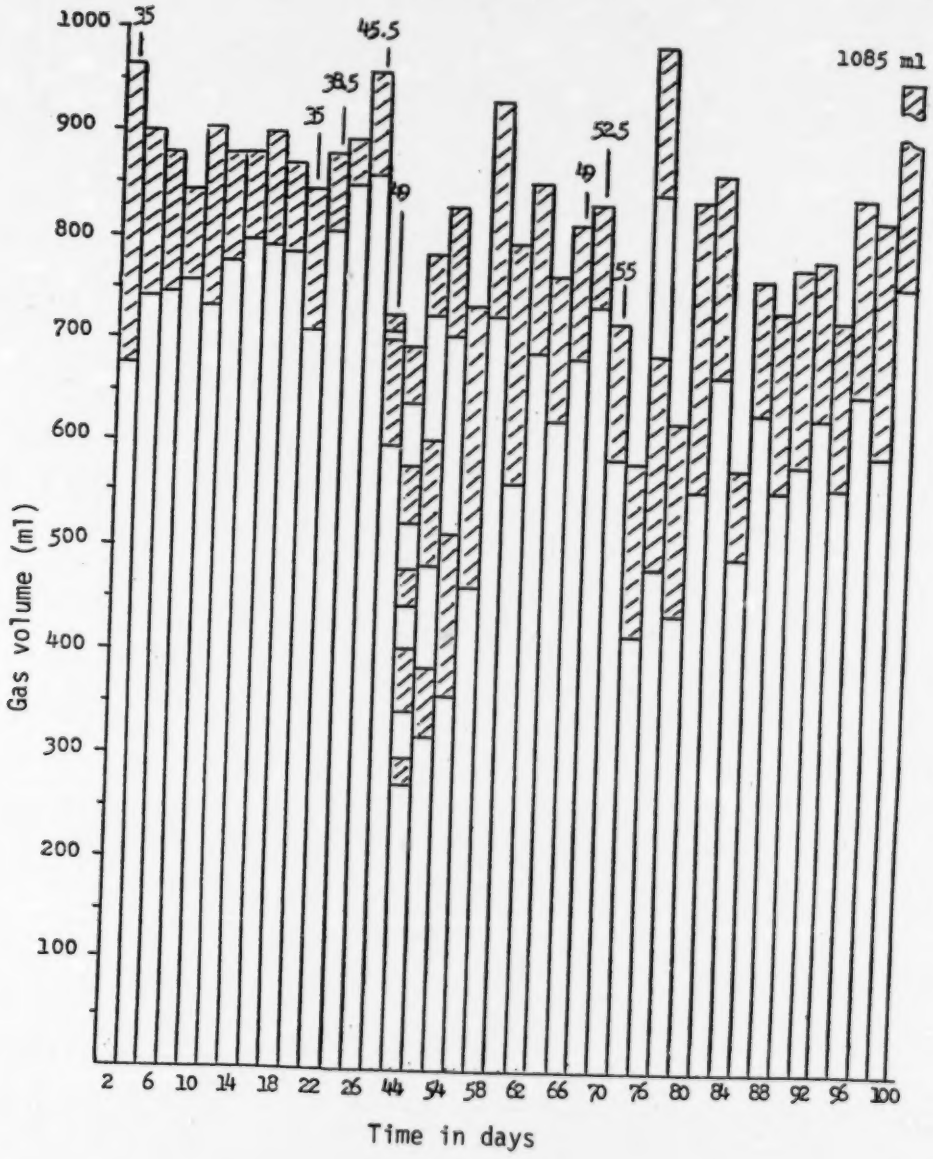


Figure 23. Gas production from unit 7B (3.5°C increment): 20 day detention time.

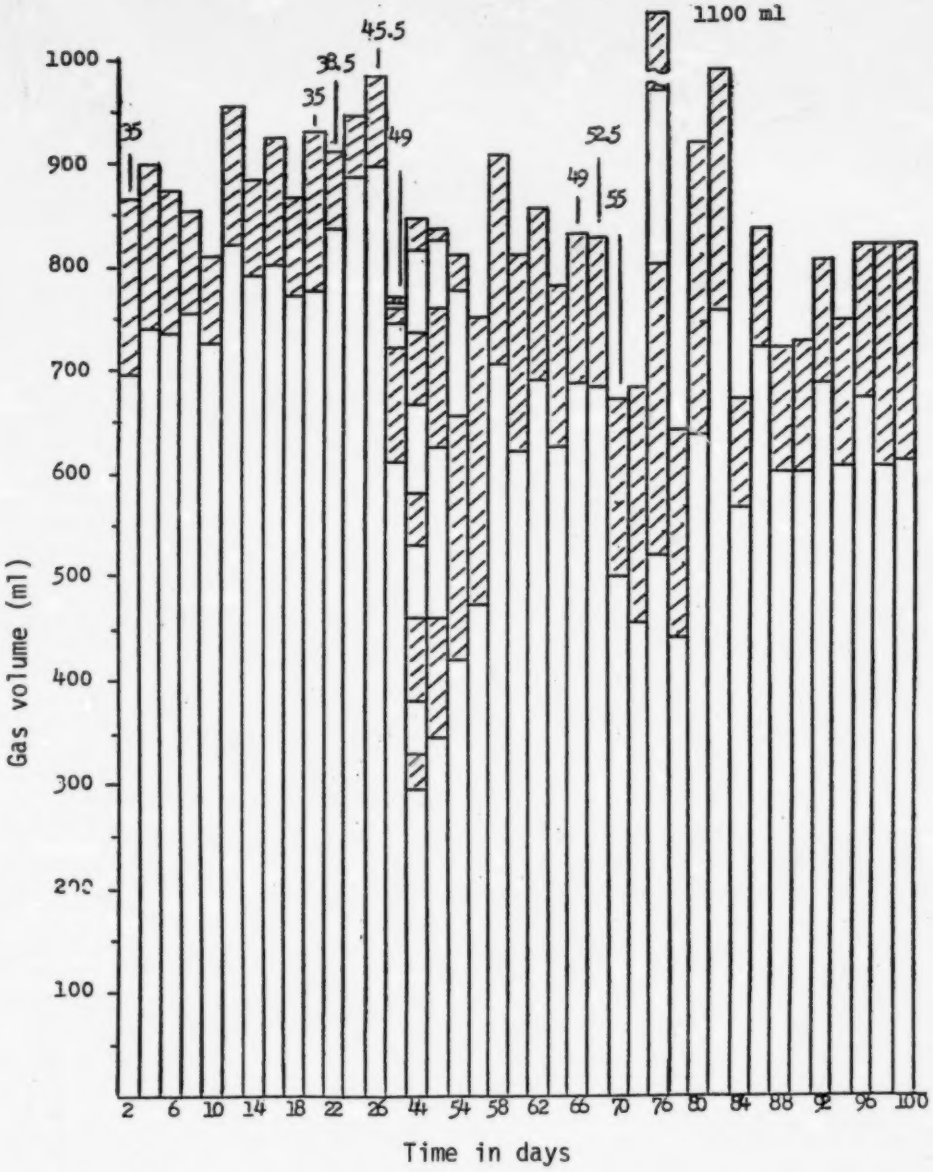


Figure 24. Temperature and volatile acids concentration versus time for unit 7A (3 5°C increment): 20 day detention time.

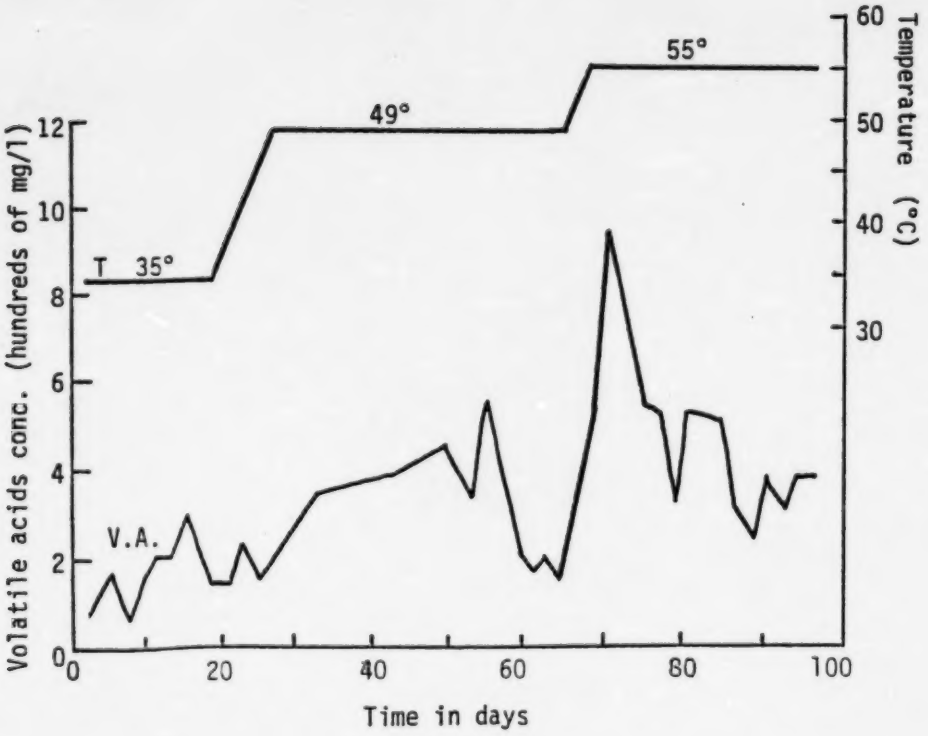


Figure 25. Temperature and volatile acids concentration versus time for unit 7B (3.5°C increment): 20 day detention time.

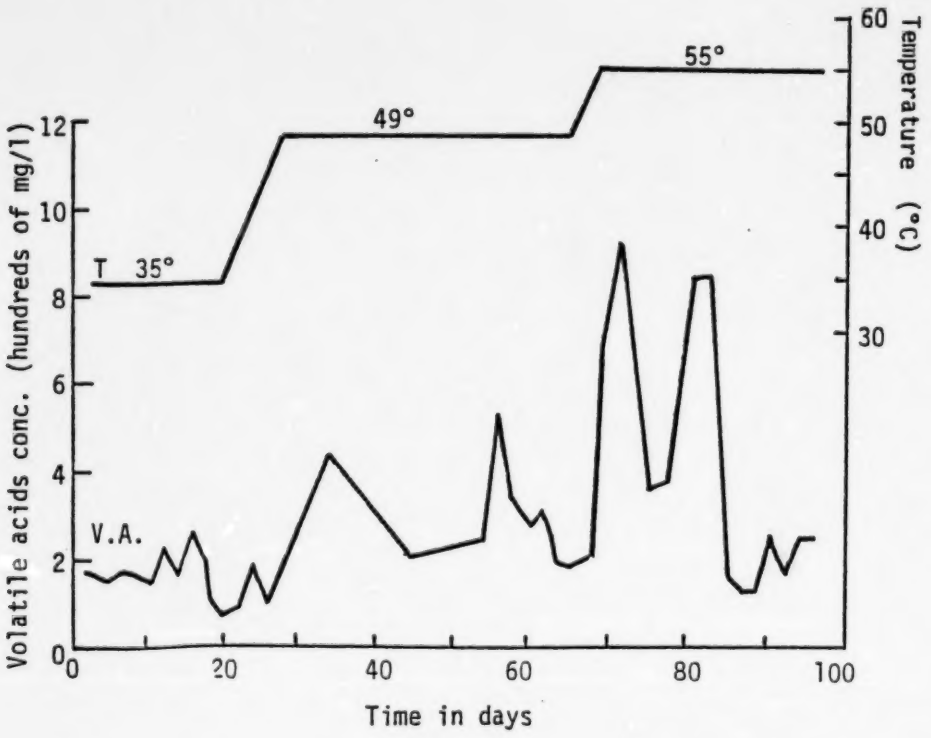


Figure 26. Gas production from unit 1A ($2^{o}C$ increment): 30 day detention time.

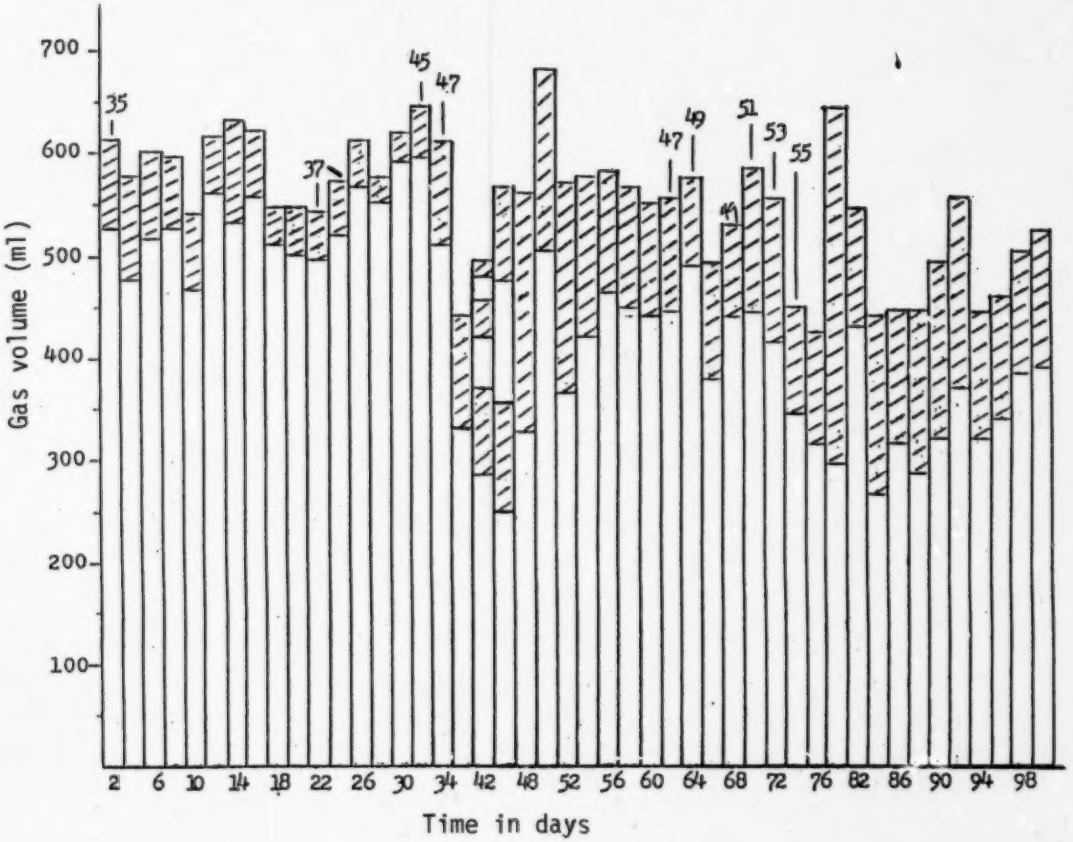


Figure 27. Gas production from unit 1B ($2^{o}C$ increment): 30 day detention time.

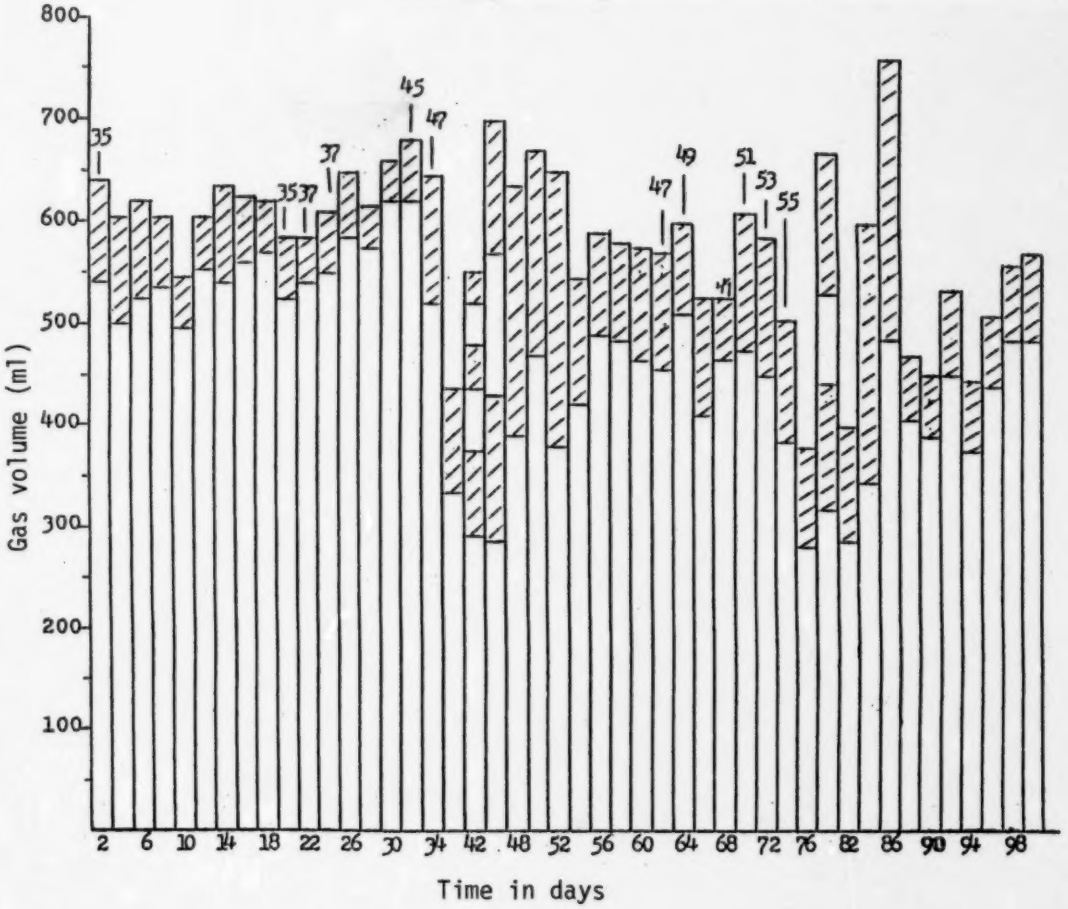


Figure 28. Temperature and volatile acids concentration versus time for unit 1A (2°C increment): 30 day detention time.

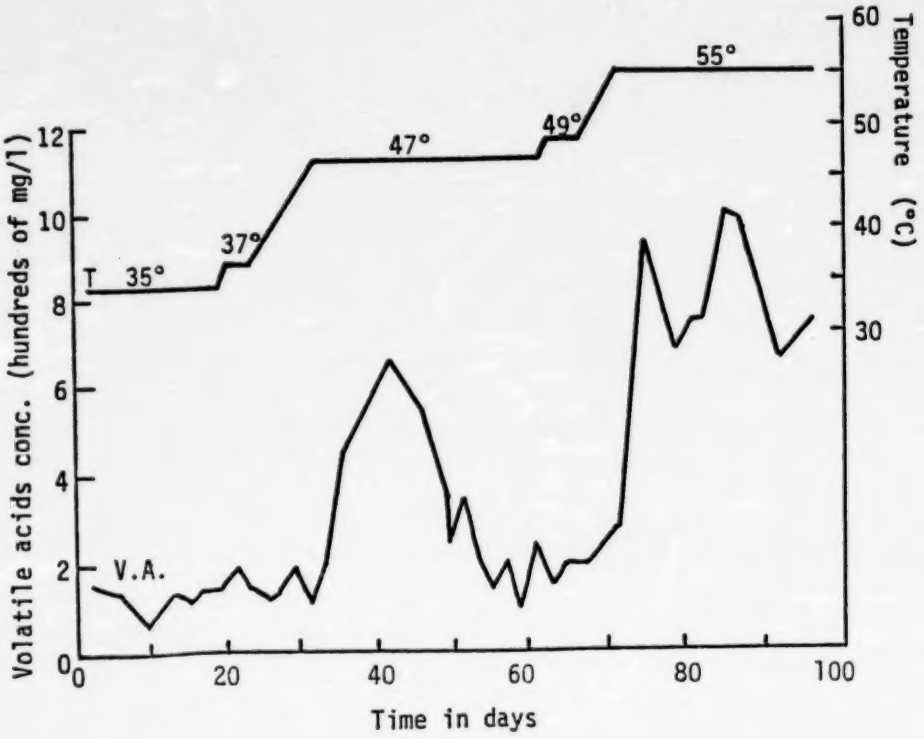


Figure 29. Temperature and volatile acids concentration versus time for unit 1B (2°C increment): 30 day detention time.

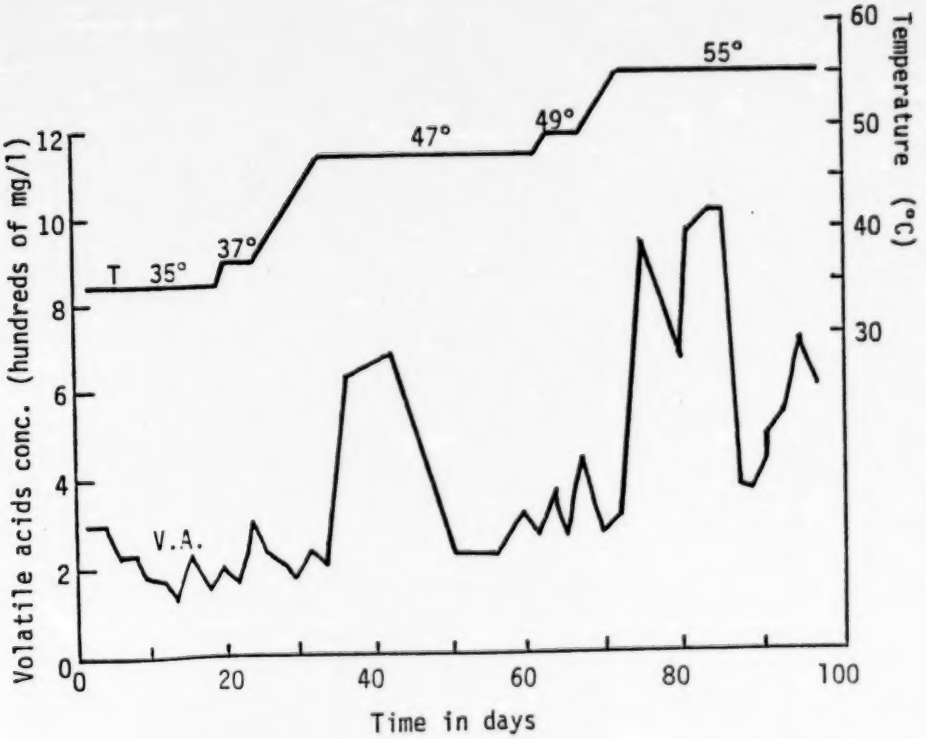


Figure 30. Gas production from unit 4A (2^{o}C increment): 20 day detention time.

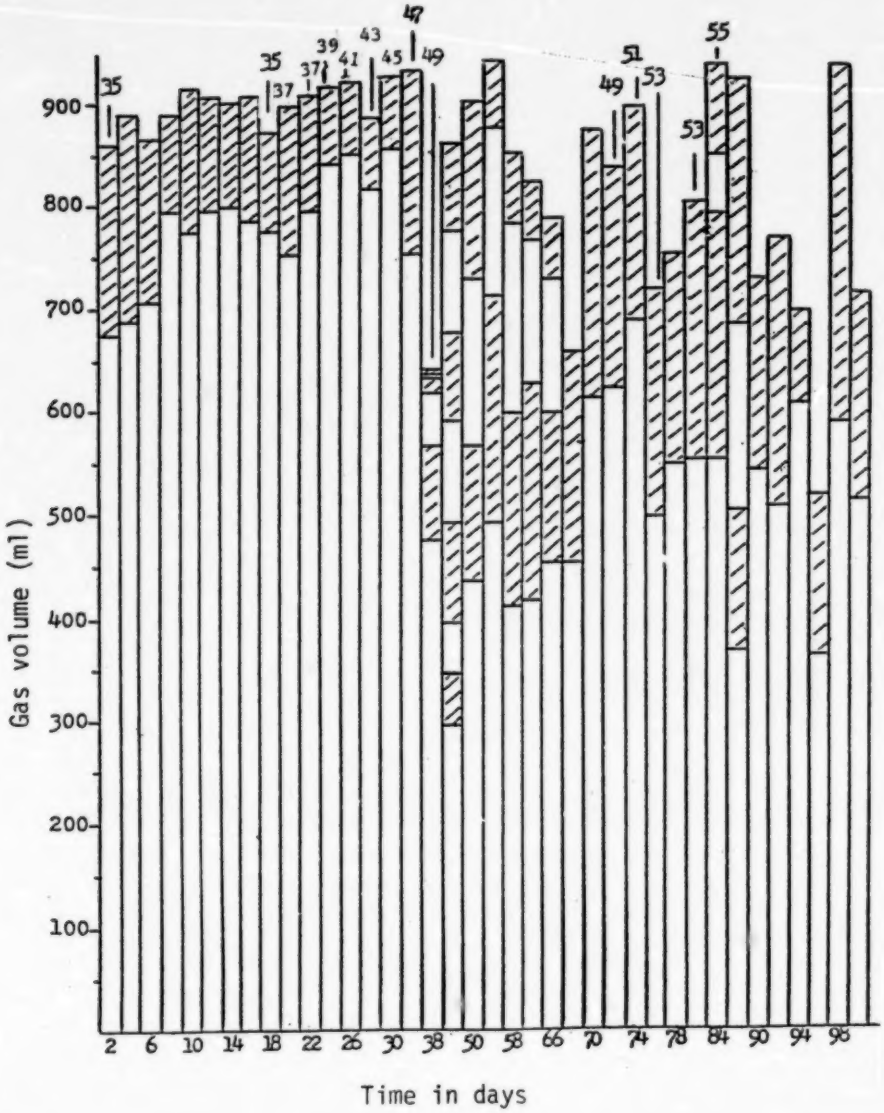


Figure 31. Gas production from unit 4B (2°C increment): 20 day detention time.

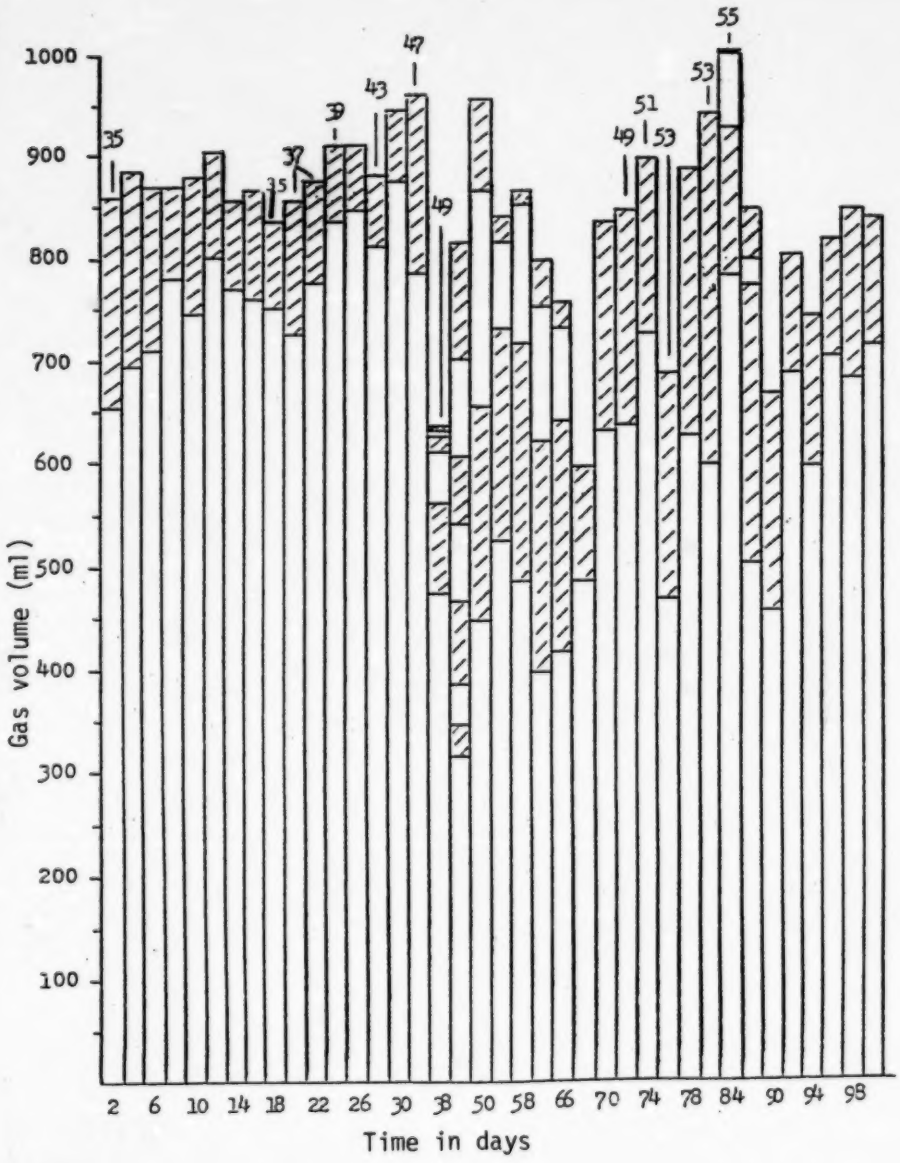


Figure 32. Temperature and volatile acids concentration versus time for unit 4A (2°C increment): 20 day detention time.

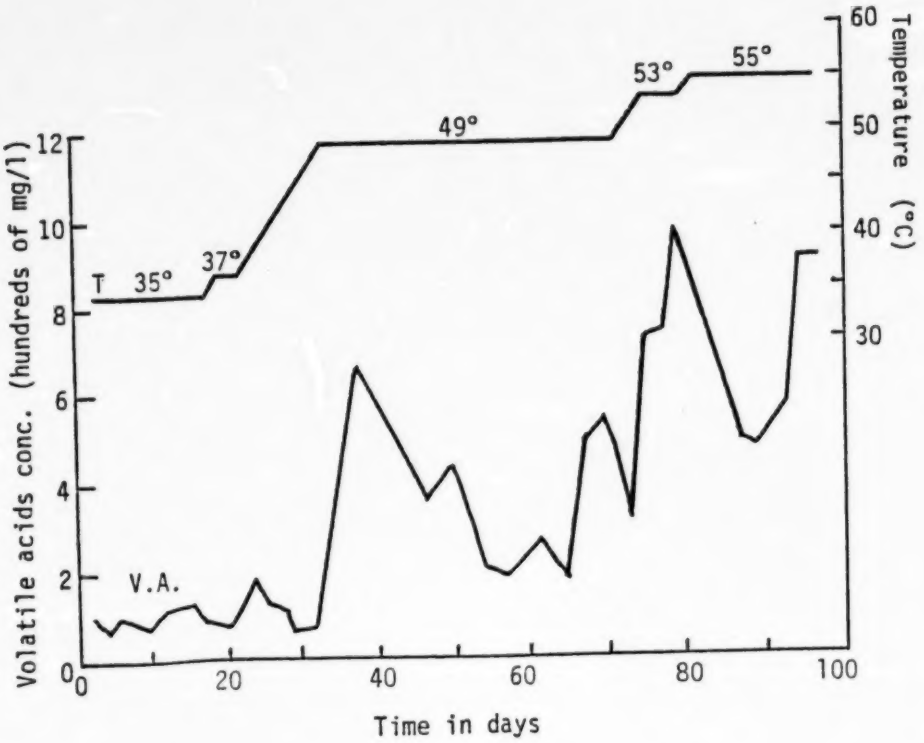


Figure 33. Temperature and volatile acids concentration versus time for unit 4B (2°C increment): 20 day detention time.

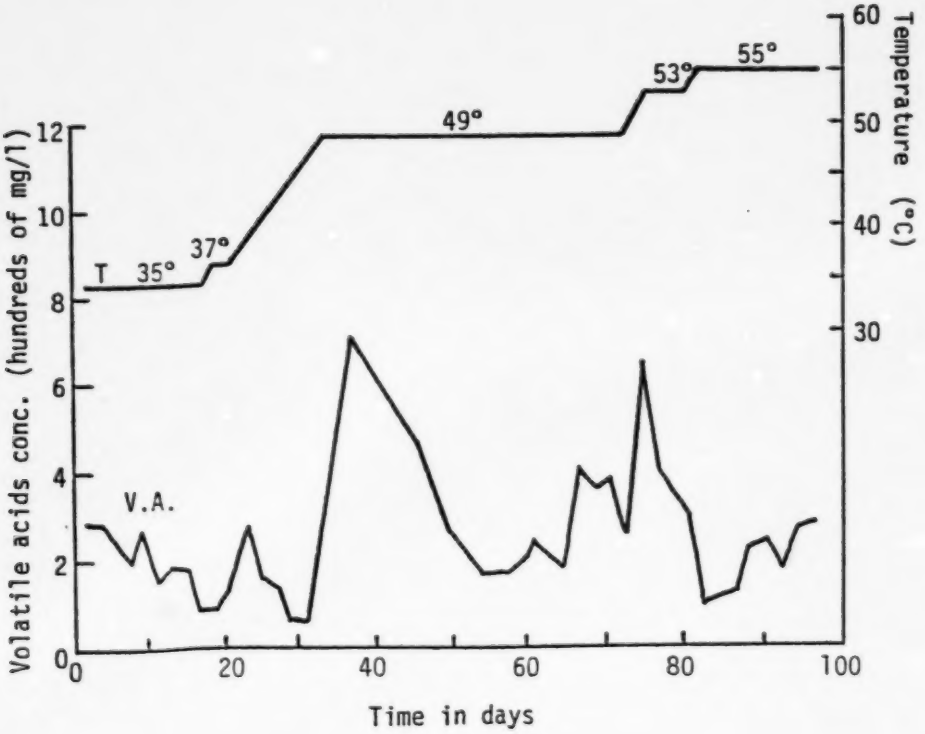
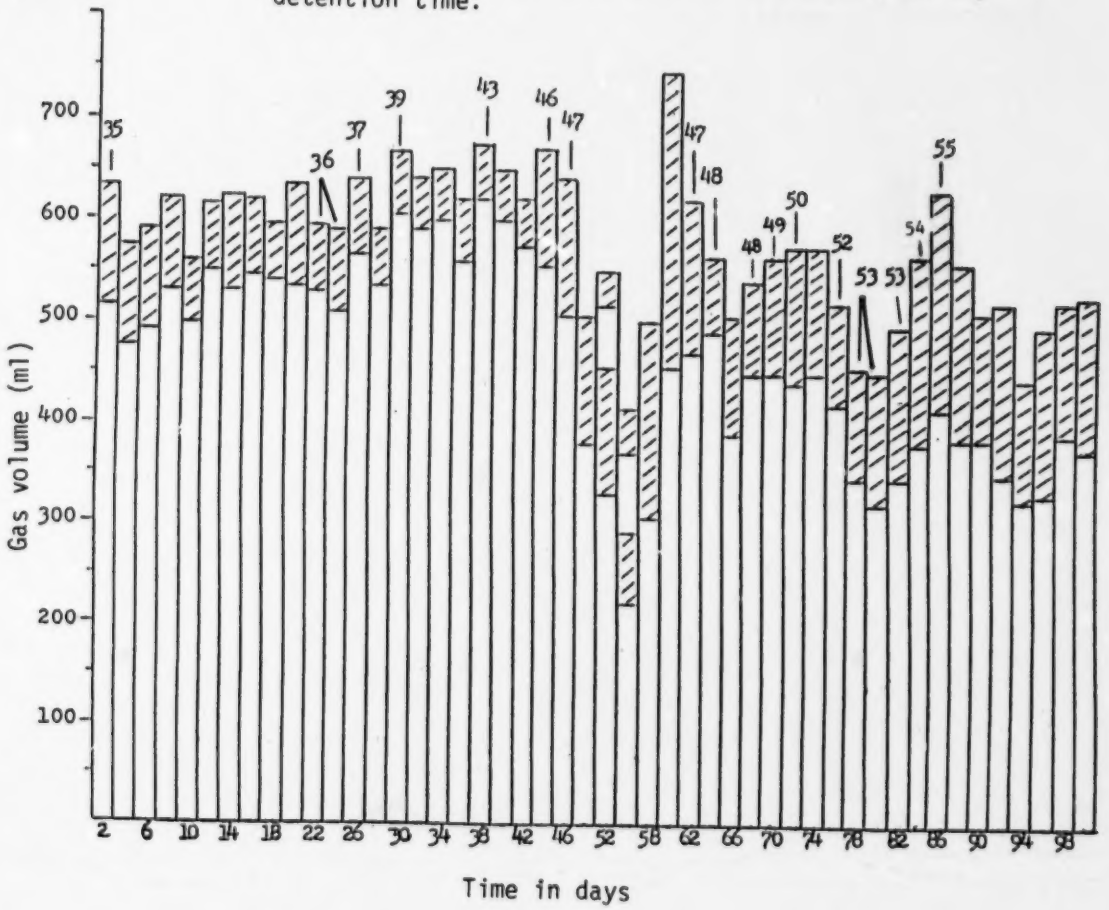


Figure 34. Gas production from unit 2A ($1^{o}C$ increment): 30 day detention time.



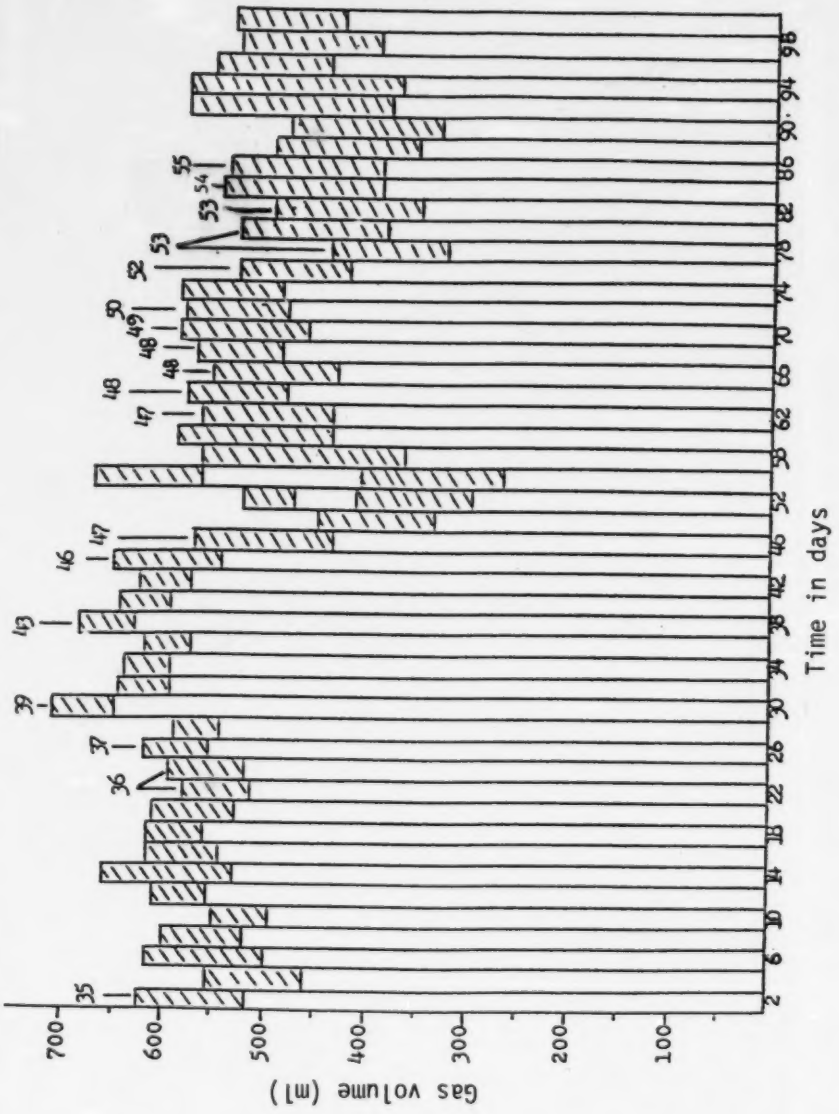


Figure 35. Gas production rom unit 2A (1^{o}C increment): 20 day detention time.

Figure 36. Temperature and volatile acids concentration versus time for unit 2A (1°C increment): 30 day detention time.

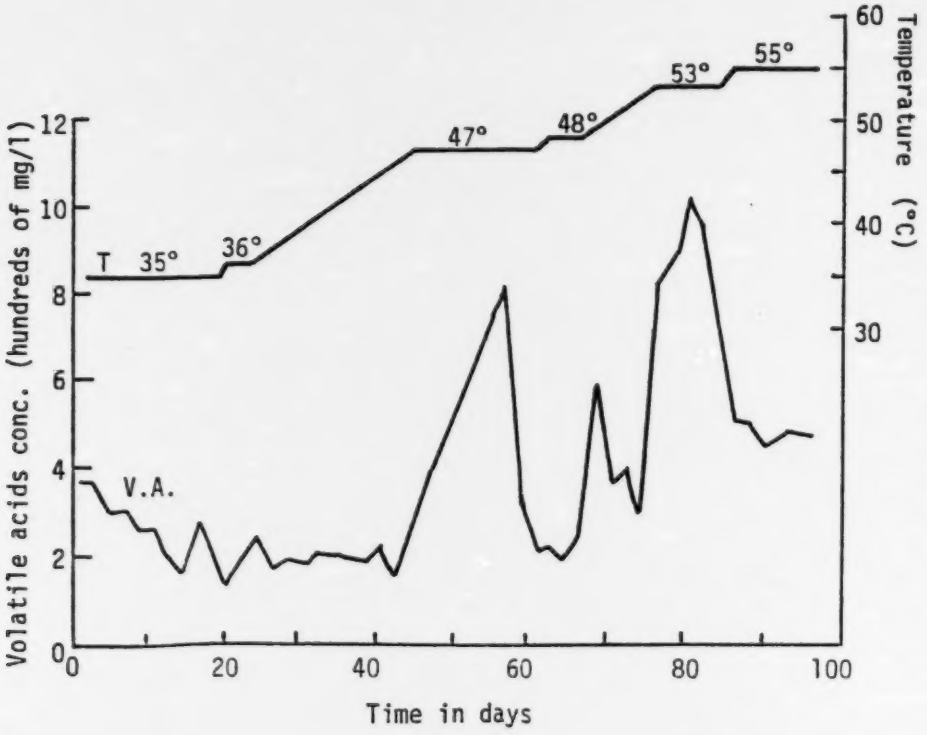
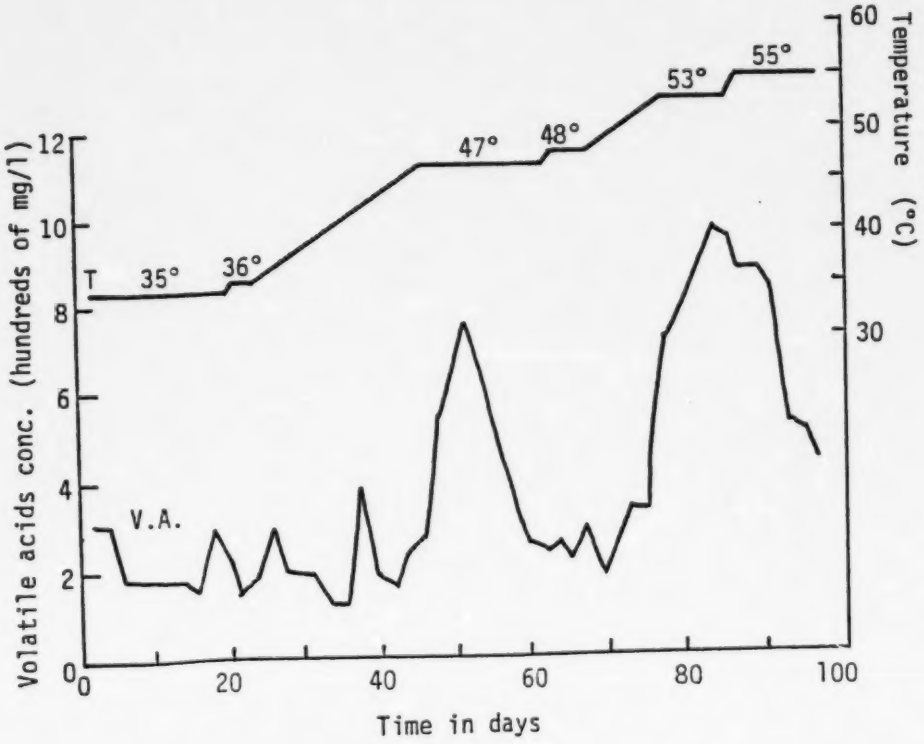


Figure 37. Temperature and volatile acids concentration versus time for unit 2B (1°C increment): 30 day detention time.



Rate of Temperature Rise = 1°C - 30 Day Detention Time

Figures 34-37 illustrate system performance under the lowest rate of temperature rise and loading stress used. Some initial effect was observed at 46°C (note change in proportion of gas between first and second day) but it was decided to go up to 47°C. At this temperature, retardation started but in only 10 days a return to the 2 day feed pattern was possible and in 6 more the temperature was increased to 48°C. The system was fed normally but held at 48°C for six days and then pushed to 53°C. The volatile acids rose sharply and increased during the rise to 53°C; but this was overcome by holding for 6 days at 53°C. After 84 days the temperature reached 55°C where satisfactory operation at the normal feeding interval was attained. Again it should be noted that gas production in the second day is a higher proportion of the total at 55°C than at 35°C.

Rate of Temperature Rise = 1°C - 20 Day Detention Time

The data presented in figures 38-41 indicate that at this detention time temperature effects were worse than at the 30 day detention time. Here the fault cannot be excessive zeal in pushing the temperature rise as it was for the 2°C units. As with the 30 day detention time units, retardation was observed at 46°C. Here it took 28 days until the normal feed pattern could be used and 4 more days till a rise to 47°C was tried. The temperature was quickly raised 51°C but this was accompanied by a rapid rise in volatile acids so the unit was held at 51°C for 4 rather than 2 days. A rapid rise to 54°C was again accompanied by a volatile acid rise. A feeding was skipped at 54°C leading to a significant fall in volatile acids. After 6 days at 54°C the unit went to 55°C and satisfactory operation seemed to be manifest.

STEADY STATE AT 55°C AND 35°C AT 20 & 30 DAY DETENTION TIMES

Once all the units discussed above had reached 55°C and exhibited satisfactory operation, it was decided to maintain these systems at the conditions reached at the end of the temperature rise rate study, and observe their operation over an extended period of time. A plot of the effluent volatile acids for the next ninety days is given in Figures 42 and 43. It can be seen that initially there was some disparity in the performance of the units. Over the first 30 to 40 days of operation some units exhibited quite good performance (Units 2A and 5A at 30-day detention time and Units 6B, 7A, and 7B at 20-day detention time). The other units exhibited an increase in volatile acids to approximately 1200 mg/l. In addition, it was noted that the gas produced in these units was rather odorous.

It was apparent that some thermophilic organisms were present in Units 2A, 5A, 6B, 7A and 7B that were not present in the other units. In order to get all of the units operating equally, it was decided to seed the poorly operating units with organisms from the units showing good operation. Consequently, on 45th day for the 20-day detention time units and the 46th day for the 30-day detention time units extra effluent was withdrawn from

Figure 38. Gas production from unit 8A ($1^{o}C$ increment): 20 day detention time.

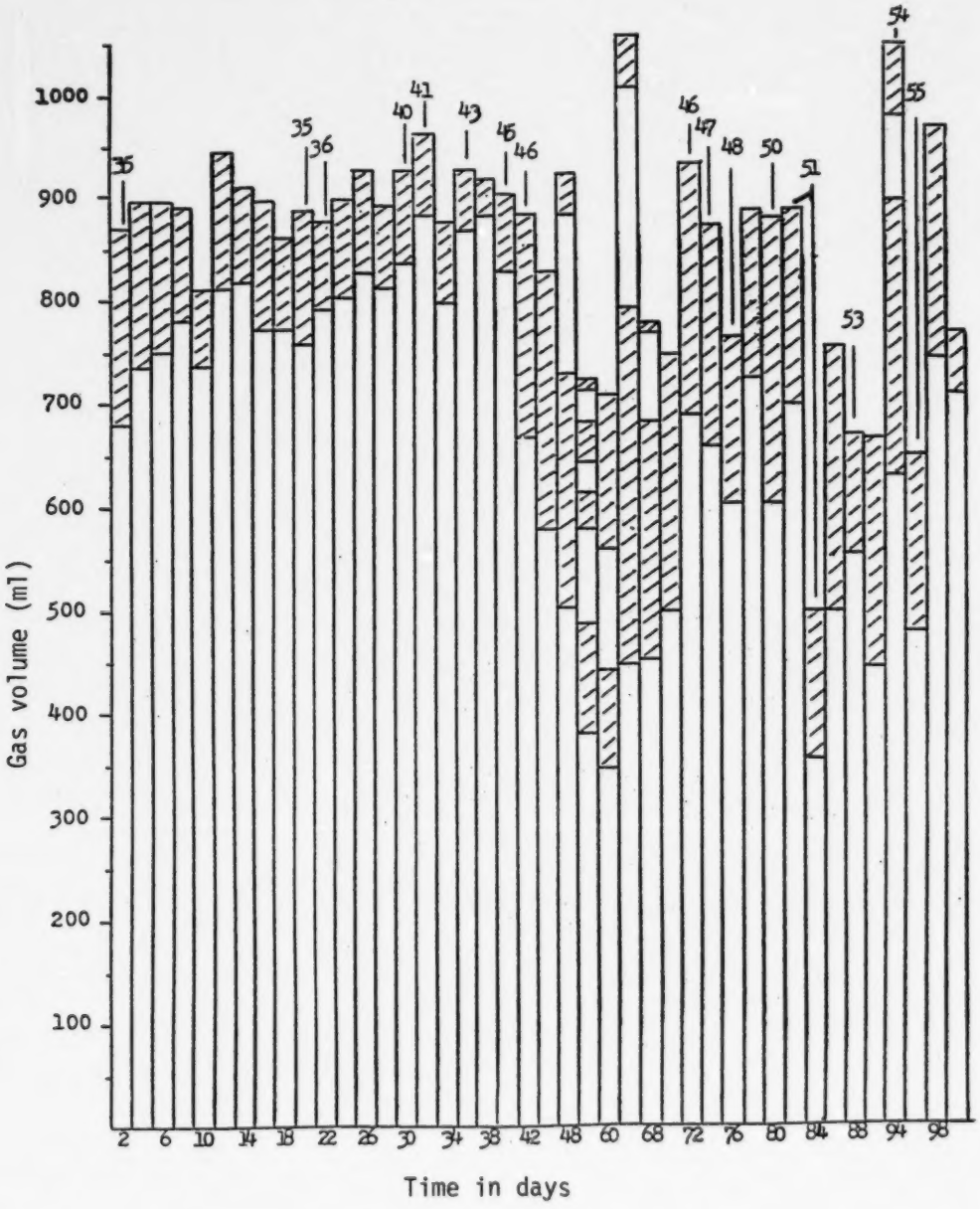


Figure 39. Gas production from unit 8B (1°C increment): 20 day detention time.

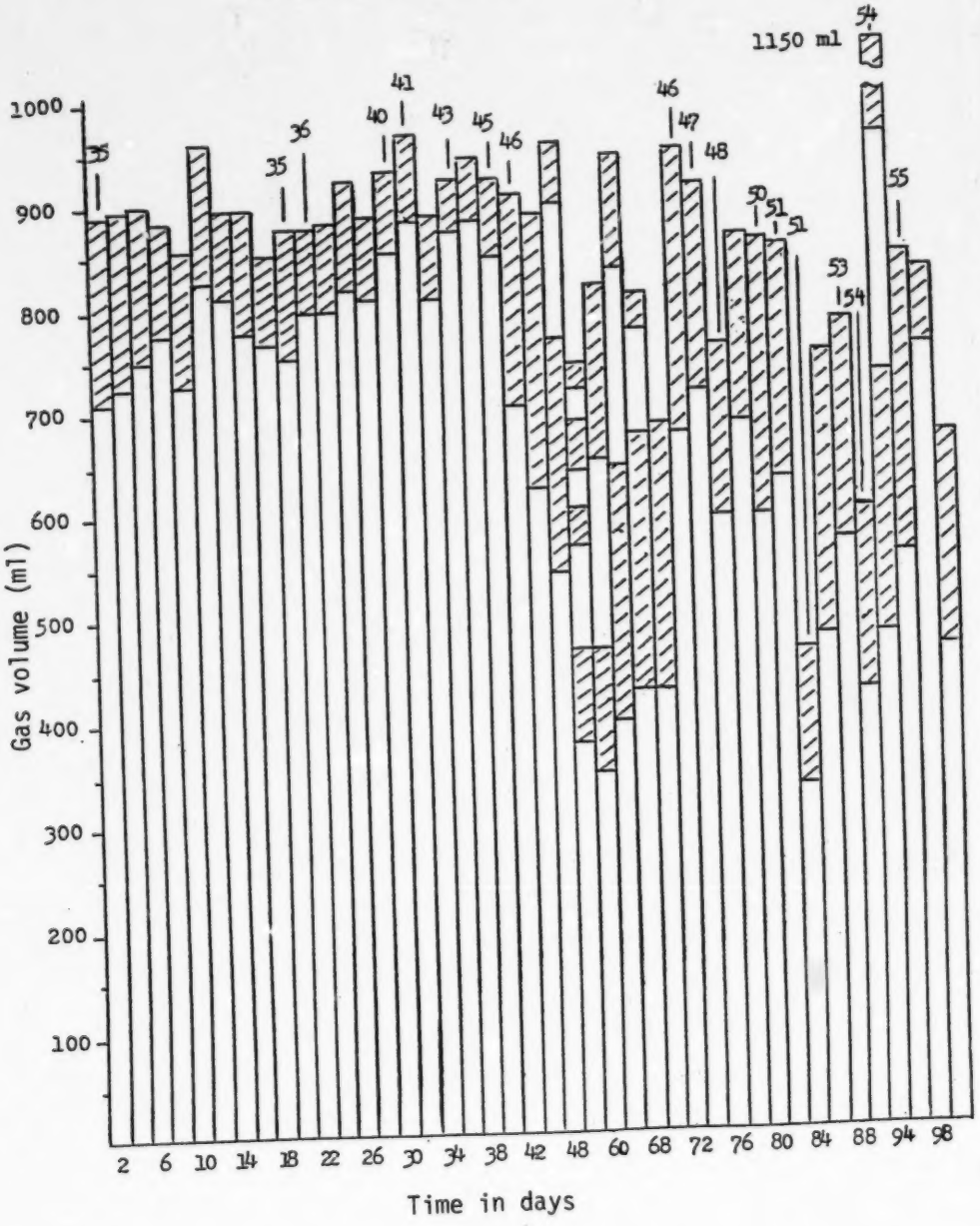


Figure 40. Temperature and volatile acids concentration versus time for unit 8A (1°C increment): 20 day detention time.

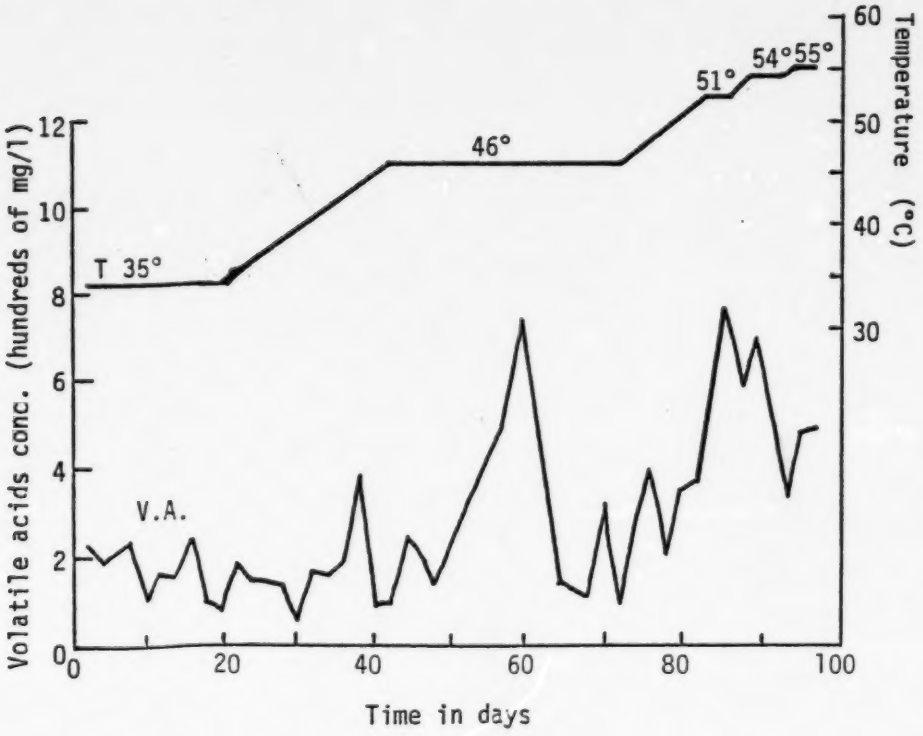


Figure 41. Temperature and volatile acids concentration versus time for unit 8B (1°C increment): 20 day detention time.

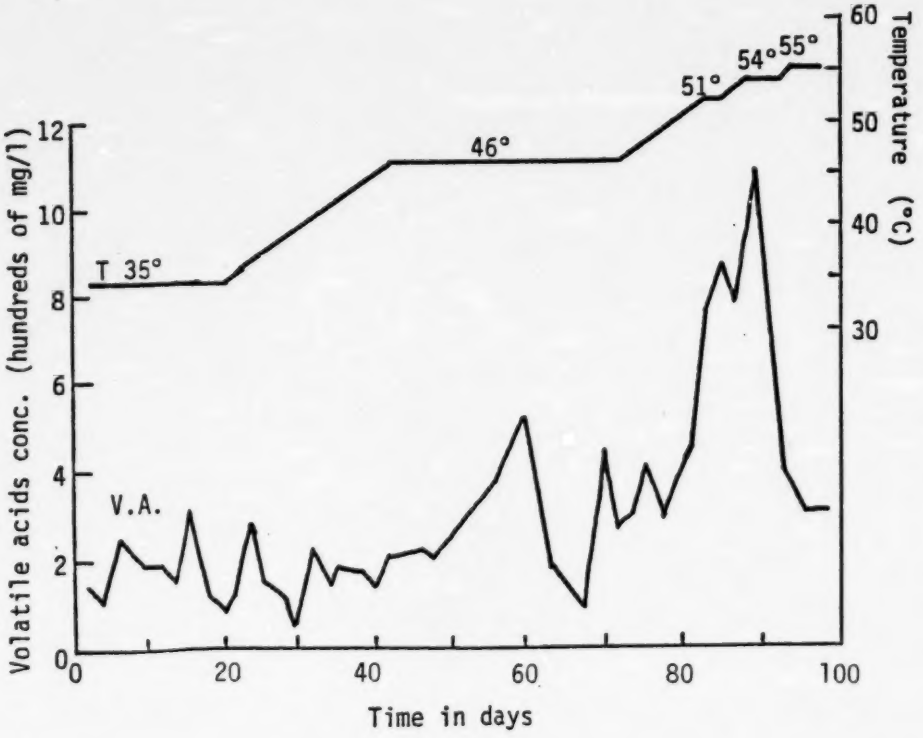


Figure 42. Volatile acids concentration versus time: 30 day detention time.

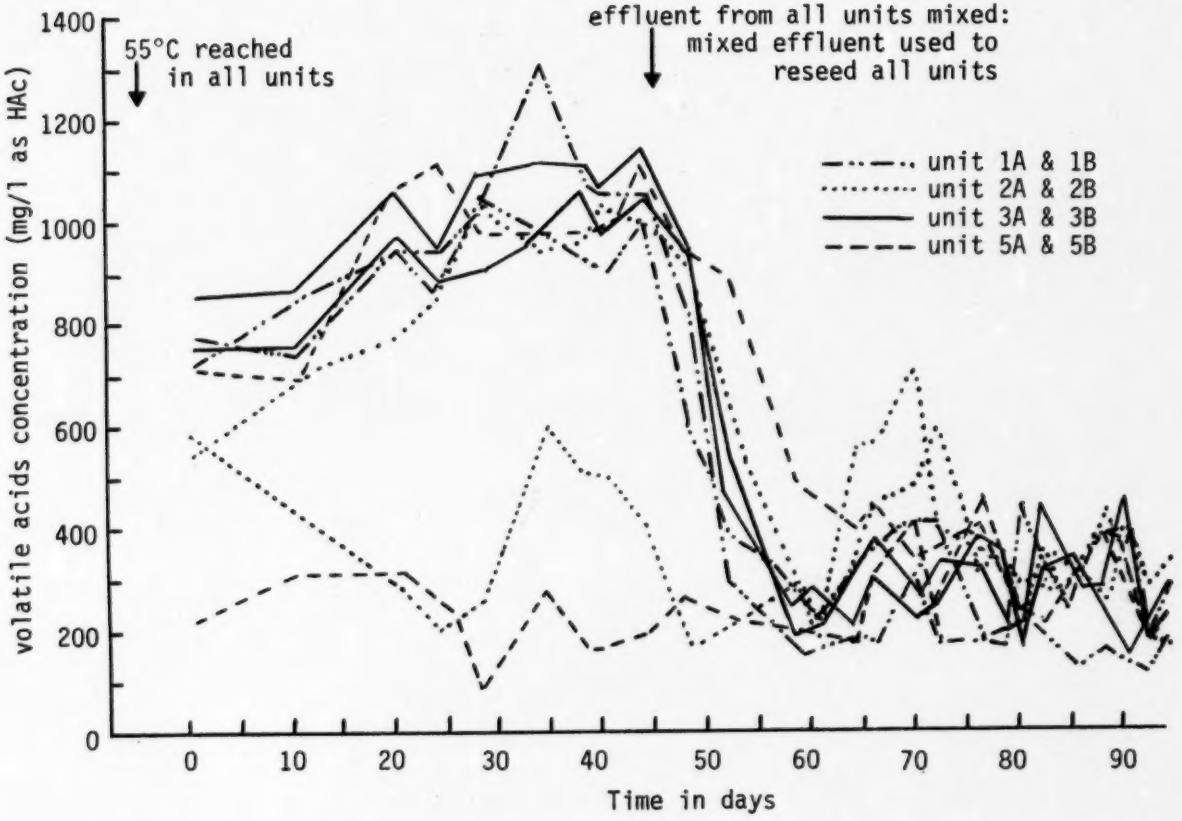
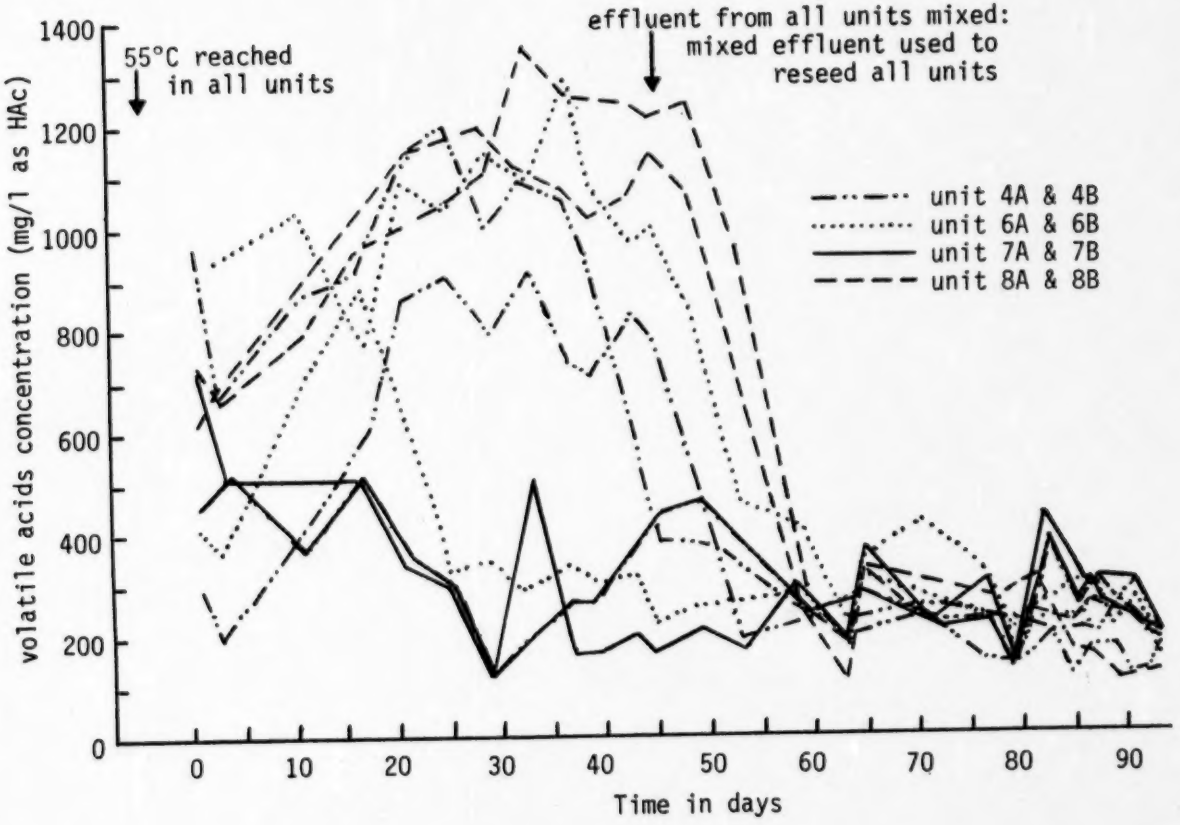


Figure 43. Volatile acids concentration versus time: 20 day detention time.



all units, pooled and anaerobically inserted back into each unit. The data in Figures 42 and 43 clearly illustrate the efficacy of this strategy. Within 10 to 15 days the volatile acid level in the effluent from all units was between 200 and 400 mg/l. For the remainder of the time of operation satisfactory performance was obtained from all units. In addition, the disagreeable odor disappeared from the gas.

Analysis of these data do not indicate any particular pattern with respect to units which retained satisfactory organisms in the transition to 55°C and those which did not. For example, in the case of Unit 2A and 2B (duplicates) one unit exhibited excellent operation, while the other exhibited marginal operation after the transition to 55°C was achieved. The same situation was manifest for Units 5A and 5B and Units 6A and 6B. Rate of temperature rise was not a factor in determination of units which achieved the proper population at 55°C; nor was detention time.

TEMPERATURE DROP STUDY

One of the concerns expressed with respect to utilization of thermophilic digestion systems is the sensitivity which they may exhibit to temperature changes. Since these units operate at temperatures much higher than mesophilic digesters it is feared that a small temperature drop will have much more of an adverse effect than it would on the lower temperature systems. To determine the effect of a temperature drop on thermophilic systems several of the 55°C units were subjected to a temperature drop. The temperature was dropped from 55°C to the new setpoint over night and then maintained at the new setpoint. The normal feed and withdrawal pattern was maintained. The performance of these systems was then monitored for the next 25 days. Units with detention times of both 20 and 30 days were used. Temperatures were reduced to: 52.5°C, 50°C, and 47.5°C. Controls were run with units maintained at 55°C and 35°C.

The results at a 30-day detention time are given in Figure 44. These data indicate that effluent volatile acids remain low in all units and were similiar to the control values. There was some early tendency for the volatile acids to increase in the unit whose temperature was reduced to 47.5°C. However, this trend was soon reversed. The data for the 20-day detention time units, given in Figure 45, exhibits a similar situation; except that both the 50°C and 47.5°C units exhibited an early tendency for volatile acids to rise. The trend was reversed for the 50°C unit, but not for the 47.5°C unit. Figure 46 is a replot of the data from the 20-day and 30-day detention time units in which the temperature was dropped to 47.5°C. This plot clearly shows the significant difference which resulted. The pattern of rise in volatile acids exhibited by the 20-day detention time unit is typical of a wash-out phenomenon. That is, the temperature reduction does not interfere with the microorganisms ability to degrade the substrate, but for some reason their ability to reproduce is impaired. Thus, the biomass in the system gradually decreases, and the effluent volatile acids gradually increase. To be sure no direct measurement of biomass was made so this is a speculation based on failure mode. It is

Figure 44. Mean volatile acids concentration versus time for units subjected to temperature drops from 55°C to 55, 52.5, 50, and 47.5°C. Units at 35°C are controls. 30 day detention time.

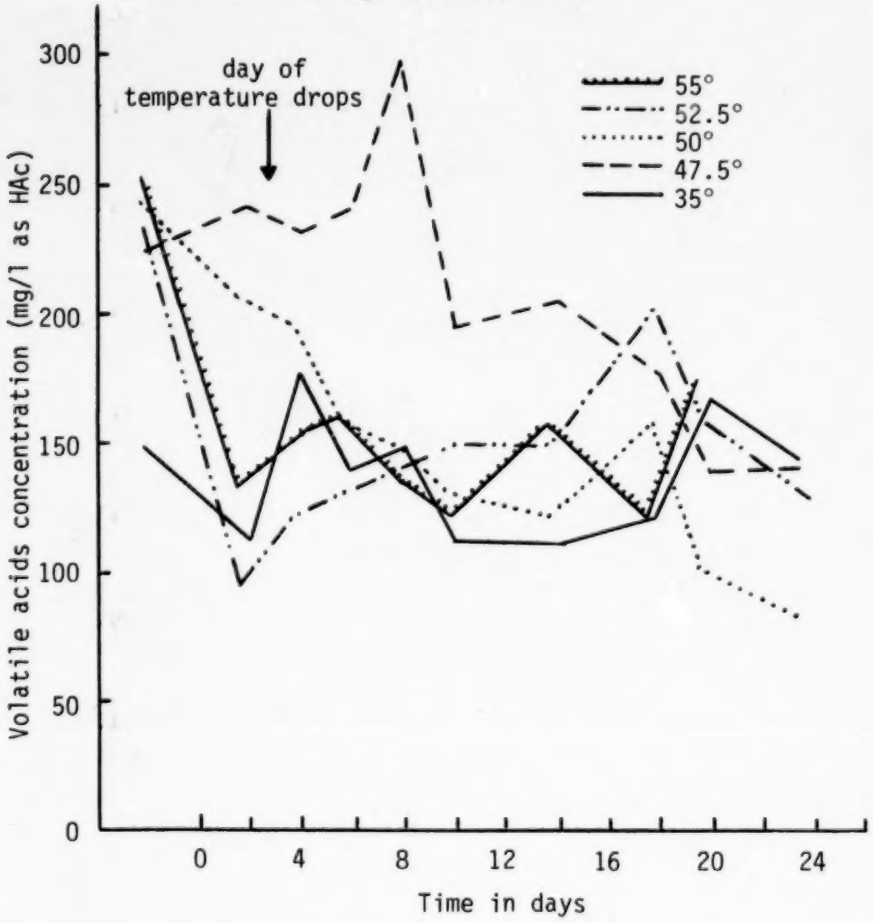


Figure 45. Mean volatile acids concentration versus time for units subjected to temperature drops from 55°C to 55, 52.5, 50, and 47.5°C. Units at 35°C are controls. 20 day detebtion time.

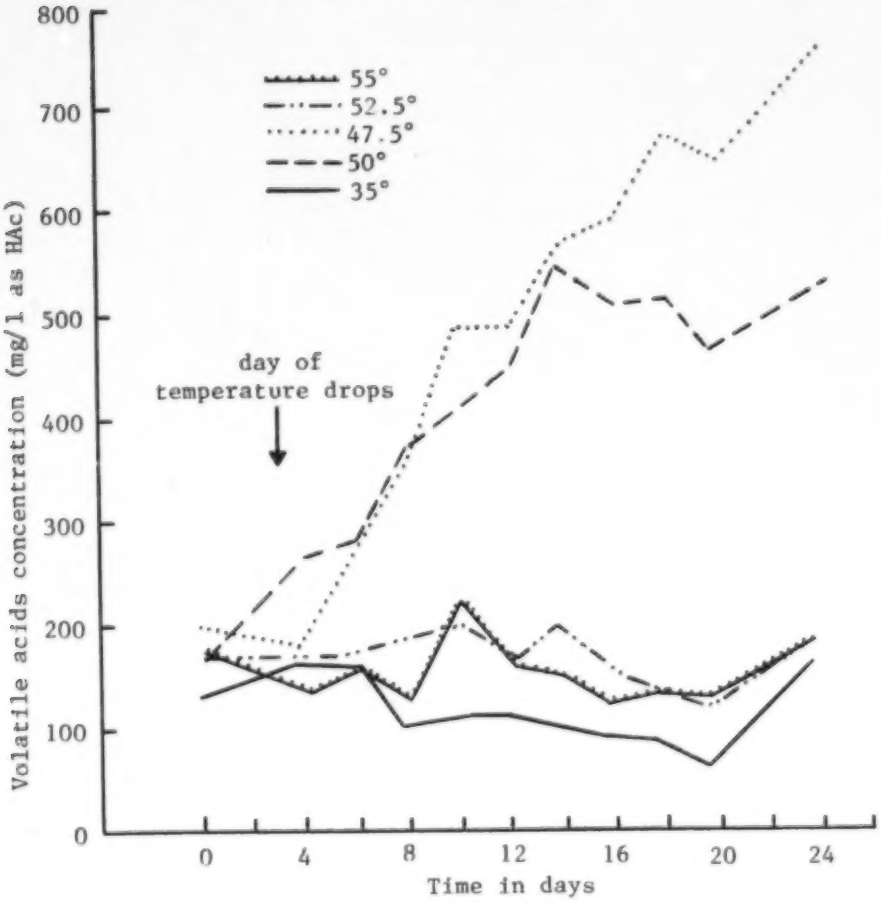
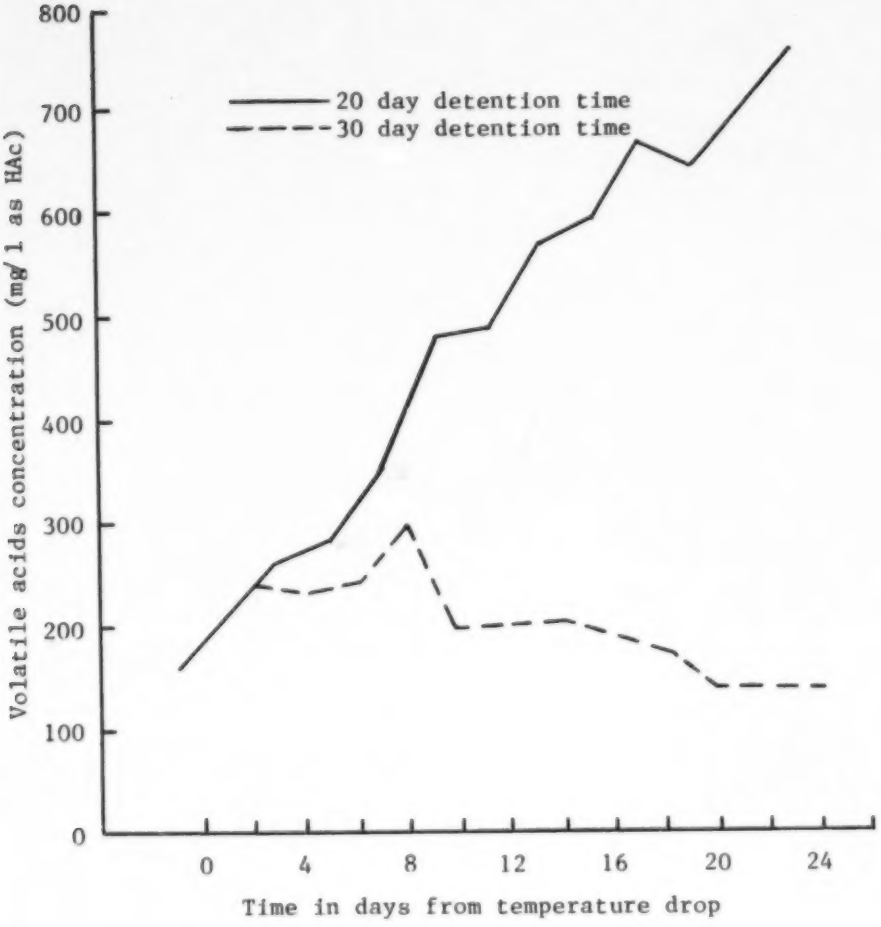


Figure 46. Comparison of mean volatile acids concentration in units at 20 day and 30 day detention times subjected to temperature drop from 55°C to 47.5°C.



possible that the 30-day detention time unit would also have gone into a failure mode if the run had been continued for a longer period of time.

Despite the problem noted above, when the temperature was dropped to 47.5°C, these data indicate that operational problems from failure of the heating system of a thermophilic digester should not be a major concern. The only adverse situation which was manifest took several weeks to develop. It is unlikely that the heating system of a digester could not be repaired in a few days. In addition, the rate of temperature drop utilized here was extreme compared to that which would occur in the field. Field digestion systems are massive tanks with high heat capacity. It is unlikely that the digestion temperature would drop by more than 1°C per day even if a complete failure of the heating system occurred in the middle of the winter.

COMPARISON OF MESOPHILIC AND THERMOPHILIC OPERATION

The units which had operated at 55°C and which were not used for a temperature drop study were used to evaluate the operation of anaerobic treatment systems at 55°C vs. 35°C for detention periods below 20 days. Detention periods used here were 15, 10 and 7.5 days. The performance at 20 and 30 day detention time was similar based on effluent volatile acids; although the mesophilic units had slightly lower volatile acids levels. It was expected that if there was a difference between mesophilic and thermophilic operation it would be most apparent at the lower detention times. Units were converted to the lower detention time and then operated at the new detention times for a period equal to at least 3 detention times. All units eventually exhibited steady-state operation in which the effluent volatile acids stayed relatively constant within a narrow range. These data are presented in Table 3 and include all of the hydraulic detention times in this study (7.5, 10, 15, 20, 30 days). These data show that as the detention time was decreased the disparity in performance between the mesophilic and thermophilic units increased. At 10 day detention time or lower the mesophilic units clearly exhibited superior performance.

TABLE 3. STEADY STATE PERFORMANCE OF THERMOPHILIC AND MESOPHILIC ANAEROBIC TREATMENT SYSTEMS

HRT	Effluent Volatile Acids mg/l	
	55°C	35°C
30	100-150	50-100
20	150-250	75-100
15	200-300	100-150
10	300-600	100-200
7.5	1000-1200	200-300

SECTION 6

DISCUSSIONS

TRANSITION TO THERMOPHILIC TEMPERATURES

The major question explored in this part of the research effort was what is the best procedure for converting a mesophilic anaerobic digester to a thermophilic unit? Table 4 presents a summary of pertinent data which can be used to address this question. For each temperature rise rate and detention time the following data are presented: time in days to first reach 55°C, time in days to achieve stable operation at 55°C, time in days to the first temperature inhibition, time in days to be able to return to a normal 2 day feed pattern after inhibition, time in days to the next temperature change after the first temperature inhibition and the number of 2 day periods during which feeding took place until 55°C was achieved. The figures presented in the table except for the first and last columns represent days after the first change from 35°C. The following major points can be deduced from this table and from Figures 2-41.

1. The slower the temperature rise the longer it takes to initially reach 55°C.

2. The rate of temperature rise has only a minor effect on the time to reach stability at 55°C.

3. Irrespective of the rate of temperature rise, a major retardation occurs when ever the temperature exceeds 45°C.

4. The effect of this retardation is less at low temperature rise rates.

5. At high temperature rise rates once acclimation to the thermophilic conditions occur, few problems are manifest.

6. At low temperature rise rates small periods of acclimation are needed as the unit proceeds from 45°C to 55°C.

7. At low temperature rise rates the unit can be fed a high percentage of time during the transition procedure.

8. At high temperature rise rates the unit can be fed only a small percentage of time during the transition period.

9. There seems to be a zone of minor retardation in the 50-55°C range.

10. Temperature changes adversely affect the methane bacteria to a much greater extent than the acid formers.

11. Temperature effects are not instantaneous. During the first feed period after 45°C is exceeded almost normal operation occurs. Retardation is manifest during the next feeding period.

12. Temperature effects are magnified at lower detention time.

TABLE 4. SUMMARY OF PERFORMANCE DURING TEMPERATURE TRANSITION FROM MESOPHILIC TO THERMOPHILIC CONDITIONS

Temp. Change-Detention Time	Time to Reach 55°C	Time to Reach Stability at 55°C	Time to First Major Inhibition	Time to Resume 2 day Feed Pattern	Time Till Next Temp. Change	# of Feeding Periods to 55°C
5-30	52	52	6	38	52	13
5-20	56	72	6	48	56	13
3.5-30	54	54	10	44	48	13
3.5-20	48	56	8	34	46	14
2-30	54	62	14	26	42	23
2-20	60	68	12	48	52	21
1-30	64	64	24	36	42	30
1-20	74	74	22	48	50	27

Overall it does not seem that the rate of temperature rise affects the speed of conversion to thermophilic conditions. A decision on the rate to use will depend on another major factor, i.e., what can be done with the raw sludge during the conversion process. If there is no alternate sludge handling procedure the slow rate of rise should be used, as for the most part, feeding of the digester can continue. If an alternate sludge handling procedure exists the rapid rise method would achieve operation at 55°C in a shorter period of time. Since operation is satisfactory between 35°C and 45°C, perhaps a combination procedure would be best; a rapid rise to 45°C followed by a slow rise to 55°C.

In this study it was observed that once the temperature increased above 45°C the units suffered retardation. The retardation was more dramatic when the temperature increment was high than when modest increments were used.The 5°C increment units virtually shut down for several weeks and then started to recover. The units with lower temperature increments did not exhibit such a complete shutdown, rather they suffered some degree of temporary retardation. All of the units eventually completely recovered and demonstrated the ability to operate satisfactorily at temperatures in the range of 45°C to 55°C. It is probable that the units contain organisms which are thermophilic, but which do not function at temperatures below

45°C. Once the temperature enters a range that these organisms can function in, they begin to function. The amount of time required to build the population of thermophiles to the level required for optimum performance was the several weeks noted above. This time period is consistent with the known doubling time of methane bacteria which is in the range of 3 to 4 days. Since most of the original seed sludge had been washed out of these units prior to starting the rise-rate study, and was replaced with mesophilic organisms which could reproduce on the substrate used, it is probable that very few thermophilic organisms were present when the temperature initially reached thermophilic levels. Thus, if domestic sewage sludge had been the feed transition to thermophilic conditions would have been easier because the units would have been continually reseeded with dormant thermophilic microorganisms. It is unlikely that the artificial substrate actually used here contained thermophiles because the Carnation Instant Breakfast is radiation sterilized by the manufacturer, and the milk used is pasturized at elevated temperatures (much higher than 55°C). Thus, the presence of thermophilic methane bacteria in the feed is unlikely.

STABILITY OF OPERATION AT 55°C

After the temperature transition to 55°C was achieved the units were maintained at this temperature for the next 3 months. It was observed that some of the units exhibited good operation while others exhibited marginal operation (volatile acids of approximately 1,000). It was found that some of the microflora required for optimum operation at 55°C did not survive the transition. Seeding from units which had this microflora restored optimum operation. Thus, while it is apparent that thermophilic organisms exist in anaerobic treatment systems which are operating at mesophilic conditions, some may have difficulty surviving the transition. Thus, some seed from a thermophilic digester exhibiting good operation may be necessary in order to insure trouble free transition to thermophilic conditions.

TEMPERATURE DROP STUDIES

The data collected indicate that a temporary temperature reduction to as low as 47.5°C will not have an adverse effect on a thermophilic system which has been operating at 55°C. A temperature drop to as low as 50°C will not have an adverse effect even if this temperature drop is permanent. The magnitude of the effect observed when the temperature drops below 50°C will depend upon the detention time of the system. Because the adverse effect noted appeared to be related primarily to washout rather than an inability of the organisms to degrade the substrate, the adverse effect is magnified at lower detention times.

COMPARISON OF MESOPHILIC VS. THERMOPHILIC OPERATION

At long detention times it was found that mesophilic and thermophilic anaerobic digestion systems exhibited similar operation; although the mesophilic systems were slightly superior. Once the detention time was reduced below 10 days significant performance advantage accrued to the mesophilic system.

REFERENCES

1. Standard Methods for the Examination of Water and Wastewater APHA, AWWA, WPCF, 15th Ed. (1985).

2. Fisher Scientific Co., Catalogue (1986), Model #1200, p. 250.